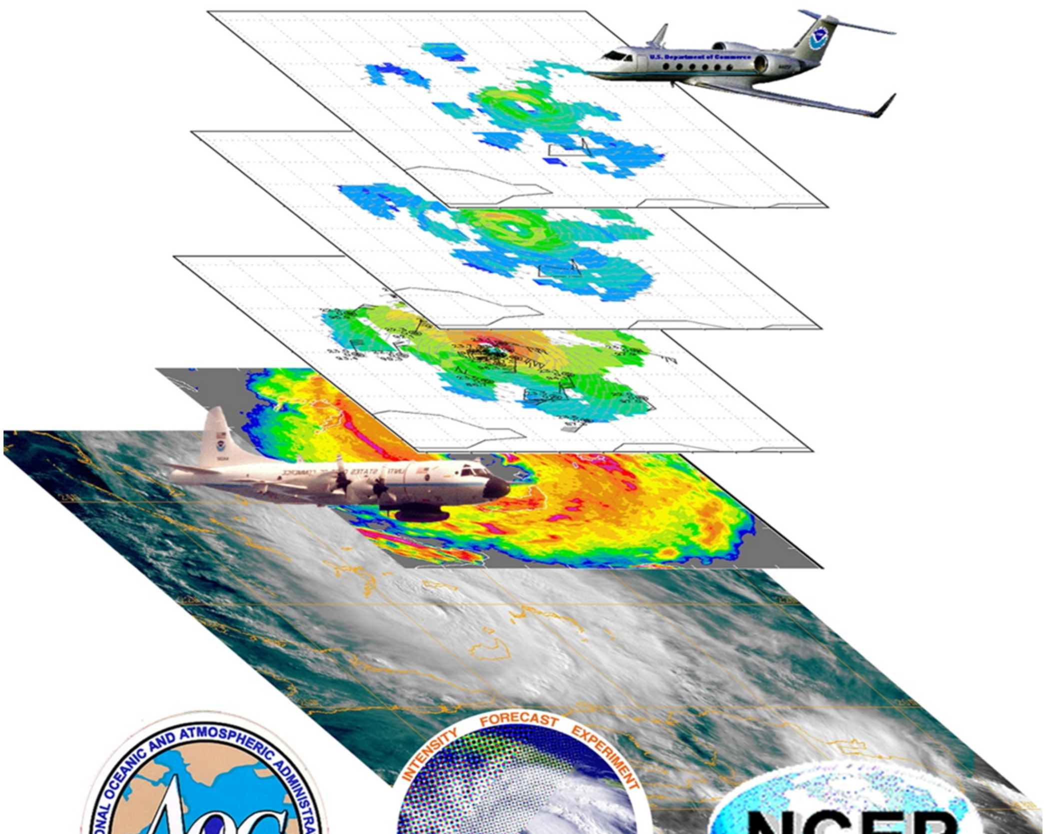
2018
Hurricane Field Program



2018 HURRICANE FIELD PROGRAM PLAN
INTENSITY FORECAST EXPERIMENT

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Atlantic Oceanographic and Meteorological Laboratory (AOML)
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2018 NOAA/AOML/HRD Hurricane Field Program - IFEX

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TAIL DOPPLER RADAR (TDR) EXPERIMENT
Pattern and Module Descriptions

Investigator(s): Paul Reasor, John Gamache (Co-PIs)

Requirements: Clear air and TCs of any intensity

SCIENCE OBJECTIVE #1: *Gather airborne Tail Doppler Radar wind measurements that permit an accurate initialization of HWRF, and also provide three-dimensional wind analyses for forecasters* [Tail Doppler Radar, TDR, Experiment]

P-3 Pattern #1: TDR

What to Target: Sample invests and tropical cyclones of interest to the NHC/EMC

When to Target: Sampling commences when tasked by EMC. Missions tasked for TDR assimilation purposes are carried out every 12 h, typically with takeoff times of 0600 and 1800 UTC.

Pattern: While TDR data can be collected whenever the P-3 is flying, the standard patterns are best used during a tasked mission. For reconnaissance, the Alpha pattern is typically employed. For TDR assimilation purposes, the Lawnmower and Square-spiral patterns are appropriate for invests and tropical depressions. For systems having a more well-defined center of circulation, the Figure-4, Rotated Figure-4, Alpha, Butterfly, and P-3 Circumnavigation patterns are all appropriate.

Flight altitude: TDR data for assimilation and analysis can be collected at most flight altitudes. Typical flight altitude is 10 kft.

Leg length or radii: The standard leg length for TDR missions is 105 n mi, but this can be adjusted as needed for land restrictions and ferry times. Legs may be shortened due to lack of scatterers, but the HRD LPS should be consulted first to ensure that other scientific objectives are not adversely impacted.

Estimated in-pattern flight duration: See the listing of standard pattern figures.

Expendable distribution: Expendables are not required. Dropsondes may be requested by NHC.

Instrumentation Notes: TDR coverage and analyses are best when straight and level flight is maintained. During tasked missions, straight leg segments (e.g., passes through the center of circulation) should not be interrupted with break-away modules. Doppler radars should be operated in a single-PRF mode, at a PRF of 2100 Hz.

P-3 Pattern #2: TDR (Clear Air)

What to Target: Clear air over open ocean conditions in a low-wind region

When to Target: At the beginning of the season, preferably during a pre-season test flight

Pattern: Straight and level flight, reversing course (Fig. TD-1). The pattern should be flown upwind and downwind, defined by the flight-level winds.

TAIL DOPPLER RADAR (TDR) EXPERIMENT
Pattern and Module Descriptions

Fig. TD-1. *Example of clear-air TDR pattern*

Flight altitude: 15–20 kft is best.

Leg length or radii: 5–10-minute segment (10–20 minutes for entire pattern)

Estimated in-pattern flight duration: 10–20 minutes

Expendable distribution: None

Instrumentation Notes: The purpose of this sea-surface module is to identify angle corrections to be applied in the P-3 TDR software for the season. The sea surface should be unobstructed by intervening scatterers and the winds should be light enough so as to yield a smooth sea state.

G-IV Pattern #1: TDR

What to Target: Sample invests and tropical cyclones of interest to the NHC/EMC

When to Target: Sampling commences when tasked by EMC. Missions tend to follow the NHC synoptic surveillance schedule, typically with a takeoff time of 0530 and/or 1730 UTC. The ability to perform storm overflights at any time is desirable, but safety concerns (e.g., the impact of intense convection on flight and lack of visual) may restrict overflight to certain conditions and times of day.

Pattern: While TDR data can be collected whenever the G-IV is flying, the standard patterns are best used during a TDR-focused mission. For TDR assimilation purposes, the Lawnmower and Square-spiral patterns are appropriate for invests and tropical depressions. For systems having a more well-defined center of circulation, the Figure-4, Rotated Figure-4, Alpha, Butterfly, and G-IV Star and Star with Circumnavigation patterns are all appropriate.

Flight altitude: TDR data for assimilation and analysis can be collected at most flight altitudes. Typical flight altitude is 40–45 kft.

Leg length or radii: The standard leg length for TDR missions is 105 n mi, but this can be adjusted as needed for land restrictions and ferry times. Legs may be shortened due to lack of scatterers, but the HRD LPS should be consulted first to ensure that other scientific objectives are not adversely impacted. For circumnavigations without a P-3 present, the radius of the innermost "circle" should be set to resolve the maximum wind region. Typically, winds can be retrieved out to 40–50 km from the aircraft.

Estimated in-pattern flight duration: See the listing of standard pattern figures

Expendable distribution: Expendables are not required

Instrumentation Notes: TDR coverage and analyses are best when straight and level flight is maintained. During tasked missions, straight leg segments (e.g., passes through the center of circulation) should not be interrupted with break-away modules. Doppler radars should be operated in a single-PRF mode, at a PRF of 3000 Hz.

G-IV Pattern #2: TDR (Clear Air)

What to Target: Clear air over open ocean conditions in a low-wind region

When to Target: At the beginning of the season, preferably during a pre-season test flight

Pattern: Straight and level flight, reversing course (Fig. TD-1). The pattern should be flown upwind and downwind, defined by the flight-level winds.

Flight altitude: 15–20 kft is best

Leg length or radii: 5-minute segment (10 minutes for entire pattern)

Estimated in-pattern flight duration: 10–15 minutes

Expendable distribution: None

Instrumentation Notes: The purpose of this sea-surface module is to identify angle corrections to be applied in the G-IV TDR software for the season. The sea surface should be unobstructed by intervening scatterers and the winds should be light enough so as to yield a smooth sea state.

SFMR EXPERIMENT
Pattern and Module Descriptions

Investigator(s): Heather Holbach (PI, FSU/NGI, AOML/HRD) and Mark Bourassa (FSU)

Requirements: *High-Incidence Angle*: wind speeds ≥ 15 m s^{-1}; *G-IV SFMR*: TS or Hurricane

SCIENCE OBJECTIVE #1: *Collect high-incidence angle (off-nadir) SFMR data in regions with different wind speeds (≥15 m s^{-1}), rain rates, storm relative quadrants, and radii from the storm center* [SFMR High Incidence Angle Measurements, HiSFMR]

P-3 Module #1: HiSFMR

What to Target: Regions of wind speeds ≥ 15 m s^{-1} with homogenous rain rates (or no rain) and wind direction (e.g. not in eye). Avoid regions with large wind speed or rain rate gradients.

When to Target: This module can be flown at any point during the flight while in the storm. If the WSRA is on the plane, the preference is to fly this module at night or when the sun is low in the sky.

Pattern: This module can be flown with any of the traditional in-storm flight patterns. The module consists of flying at least 3 consecutive circles at a given roll angle. Roll angles to be sampled are 15°, 30°, and 45°. If time allows, it is preferable to fly 5 consecutive circles at 45°. Best to begin circles by turning upwind for station keeping.

Flight altitude: 7–12 kft

Leg length or radii: Any

Estimated in-pattern flight duration: 3 circles at 15° takes ~17 min., 3 circles at 30° takes ~7 min., and 3 (5) circles at 45° takes ~4.5 (~7) min. for a total time of ~28.5 (~31) min. If time is a concern, remove 15° circles for a total time of ~11.5 min for 3 circles each at 30° and 45° or ~14 min for 3 circles at 30° and 5 circles at 45°.

Expendable distribution: Release a dropsonde/AXBT combo at the beginning of the module. If no AXBTs are available, this module can still be flown while only releasing a dropsonde at the beginning of the module.

Instrumentation Notes: Use standard SFMR set-up. Important to maintain as constant of a roll angle, pitch angle, and altitude as possible. Ideal to fly this module while the WSRA is also operating and gathering surface wave data. However, any data collected is useful as long as there is a dropsonde for comparison.

SFMR EXPERIMENT
Pattern and Module Descriptions

SCIENCE OBJECTIVE #2: *Sample the wind speed and rain rate from the G-IV SFMR in coordination with the P-3 SFMR* [G-IV SFMR Validation]

P-3 Module #1: G-IV SFMR Validation

What to Target: Sample various wind and rain regions within a tropical cyclone, including light (< 20 m s^{-1}), moderate (20–33 m s^{-1}), and strong wind speed regions (> 33 m s^{-1}). This strategy will depend on the strength of the TC.

When to Target: Select a point along a portion of the flight pattern (whether part of the circumnavigation ring, a downwind leg, or inbound/outbound radial pass) for the G-IV to match. The P-3 and G-IV need to be traveling on the same heading for ~20–25 n mi on either side of the module center point.

Pattern: P-3 Circumnavigation is preferred to more easily match G-IV. Other patterns are acceptable as long as a small portion of the pattern can overlap with the G-IV.

Flight altitude: 10–12 kft

Leg length or radii: Maximum of ~45 n mi, centered on location where the G-IV is directly above the P-3.

Estimated in-pattern flight duration: ~ 6–10 minutes for each overlap

Expendable distribution: 1 dropsonde at module center when G-IV directly above the P-3 (required); 2 additional dropsondes at ~10 n mi on either side of the center point (optional).

Instrumentation Notes: Use standard SFMR set-up. Also, ensure that the upward looking SFMR is working and collecting data.

G-IV Module #1: G-IV SFMR Validation

What to Target: Same as P-3 pattern.

When to Target: Because this module depends more on aircraft coordination rather than a specific storm structure or environmental variable, any point in the TC development is acceptable. Various radial and azimuthal positions are desirable, depending on the structure of the TC and limitations of the aircraft. The P-3 and G-IV need to be traveling on the same heading for ~20–25 n mi on either side of the module center point. We would also prefer the G-IV fly at the lower end of its allowable operating speed to provide more time of overflight with the P-3.

Pattern: Preferred G-IV Circumnavigation (either hexagon or octagon). Most other patterns are acceptable as well as long as they can overlap with the P-3 for a short period.

Flight altitude: 40–45 kft

Leg length or radii: Maximum of ~60 n mi, centered on location where the G-IV is directly above the P-3.

Estimated in-pattern flight duration: ~6–10 minutes for each overlap

Expendable distribution: None

Instrumentation Notes: Use the standard SFMR instrument set-up

GENESIS STAGE EXPERIMENT
Pattern and Module Descriptions

Investigator(s): Ghassan Alaka, Jon Zawislak (Co-PIs), Paul Reasor, Jason Dunion, Alan Brammer (SUNY Albany), Chris Thorncroft (SUNY Albany), Mark Boothe (Naval Postgraduate School, NPS), Michael Montgomery (NPS), Tim Dunkerton (Northwest Research Associates, NWRA), Blake Rutherford (NWRA) (Co-Is)

Requirements: Pre-genesis disturbances (pre-TDs), including NHC-designated "Invests"

SCIENCE OBJECTIVE #1: *To investigate the precipitation modes that are prevalent during the genesis stage and the response of the vortex to that precipitation organization*
[Precipitation Mode, PMODE]

P-3 Pattern #1: PMODE

What to Target: Sample the mesoscale convective burst area and/or mid-level circulation of a pre-TD or "Invest"

When to Target: Every 12 h, preferably in coordination with a corresponding G-IV mission flying the surrounding environment (for other Genesis Stage objectives)

Pattern: Standard Single (repeated), or Rotated Figure-4

Flight altitude: 10–12 kft

Leg length or radii: 105 n mi (can be adjusted for the size of the precipitating area)

Estimated in-pattern flight duration: ~ 5 h [for repeated Single-4, or Rotated Fig. 4]

Expendable distribution: Standard dropsonde locations

Instrumentation Notes: Use straight flight legs as safety permits. Inbound-outbound passes should be uninterrupted. DWL should be downward looking, 20° off nadir.

G-IV Pattern #1: PMODE

What to Target: Sample the mesoscale convective burst area and/or mid-level circulation of a pre-TD or "Invest"

When to Target: Every 12 h, when P-3 not available and G-IV not fulfilling other Genesis Stage objectives

Pattern: Standard Single Figure-4 (repeated), or Rotated Figure-4

Flight altitude: 40–45 kft

Leg length or radii: 105 n mi (can be adjusted for the size of the precipitating area)

Estimated in-pattern flight duration: ~ 5 h [for repeated, Single-4, or Rotated Fig. 4]

Expendable distribution: Standard dropsonde locations

Instrumentation Notes: None

GENESIS STAGE EXPERIMENT
Pattern and Module Descriptions

SCIENCE OBJECTIVE #2: *To investigate the importance of the pouch, including the shear sheath, which tends to indicate a tropical storm, and its relationship to a low-level circulation and organized deep convection within the pouch* [Pouch]

P-3 Pattern #1: Pouch

What to Target: The wave-pouch exhibiting scattered convective activity without much organized convective activity. This would the ideal mission investigating the wave pouch, until the center is defined.

When to Target: Every 12 h

Pattern: Standard Lawnmower; extend east-west legs an additional degree longitude (~5 deg. longitude total)

Flight altitude: 20,000 ft

Leg length or radii: 300 n mi east-west legs (modified from standard)

Estimated in-pattern flight duration: ~ 5 h

Expendable distribution: Modify standard dropsonde locations for Lawnmower by having 6 drops equally spaced on each east-west leg (~1 deg. spacing) for 24 total drops in the Lawnmower; also 3 drops, one every 1 deg., inbound prior to arrival at IP and heading outbound after exiting the pattern.

Instrumentation Notes: None

P-3 Pattern #2: Pouch

What to Target: The wave-pouch of the disturbance, when the center is better defined

When to Target: Every 12 h [*optimal*] or 24 h [*minimal*]

Pattern: Standard Square-spiral

Flight altitude: 20,000 ft

Leg length or radii: N/A

Estimated in-pattern flight duration: ~ 5 h 50 min

Expendable distribution: Modify standard dropsonde locations for the Square-spiral by having a dropsonde at ~1 deg. spacing, for 26 total drops in square-spiral; also 3 drops, one every 1 deg., prior to arrival at IP and after exiting the pattern.

Instrumentation Notes: None

GENESIS STAGE EXPERIMENT
Pattern and Module Descriptions

G-IV Pattern #1: Pouch

What to Target: The wave-pouch exhibiting scattered convective activity without much organized convective activity. This would the ideal mission investigating the wave pouch, until the center is defined.

When to Target: Every 12 h [*optimal*] or 24 h [*minimal*]

Pattern: Standard Lawnmower; extend east-west legs an additional degree longitude (~5 deg. longitude total)

Flight altitude: 40–45 kft

Leg length or radii: 300 n mi east-west legs (modified from standard)

Estimated in-pattern flight duration: ~ 3 h

Expendable distribution: Modify standard dropsonde locations for Lawnmower by having 6 drops equally spaced on each east-west leg (~1 deg. spacing) for 24 total drops in the Lawnmower; also 3 drops, one every 1 deg., inbound prior to arrival at IP and heading outbound after exiting the pattern.

Instrumentation Notes: None

G-IV Pattern #2: Pouch

What to Target: The wave-pouch of the disturbance, when the center is better defined

When to Target: Every 12 h [*optimal*] or 24 h [*minimal*]

Pattern: Standard Square-spiral

Flight altitude: 40–45 kft

Leg length or radii: N/A

Estimated in-pattern flight duration: ~ 3 h 20 min

Expendable distribution: Modify standard dropsonde locations for the Square-spiral by having a dropsonde at ~1 deg. spacing, for 26 total drops in square-spiral; also 3 drops, one every 1 deg., prior to arrival at IP and after exiting the pattern.

Instrumentation Notes: None

GENESIS STAGE EXPERIMENT
Pattern and Module Descriptions

SCIENCE OBJECTIVE #3: *To investigate the favorability in both dynamics (e.g., vertical wind shear) and thermodynamics (e.g., moisture) for tropical cyclogenesis in the environment near a pre-TD, especially the downstream environment* [Favorable Air Mass, FAM]

G-IV Pattern #1: FAM

What to Target: The environment west/northwest of an easterly wave, especially if dry air is detected

When to Target: Every 12 h [*optimal*] or 24 h [*minimal*]

Pattern: Standard Lawnmower (see Fig. GN-1)

Flight altitude: 40–45 kft

Leg length or radii: Long legs modified to be 600 n mi (or greater if time, resources available), short legs to 150 n mi

Estimated in-pattern flight duration: ~ 5 h

Expendable distribution: Standard Lawnmower, with drops every 150 n mi

Instrumentation Notes: None

P-3 Pattern #1: FAM

What to Target: The environment west/northwest of an easterly wave, especially if dry air is detected

When to Target: Every 12 h [*optimal*] or 24 h [*minimal*]

Pattern: Standard Lawnmower

Flight altitude: 20,000 ft

Leg length or radii: Standard Lawnmower

Estimated in-pattern flight duration: ~ 4 h 20 min

Expendable distribution: Standard dropsonde locations

Instrumentation Notes: None

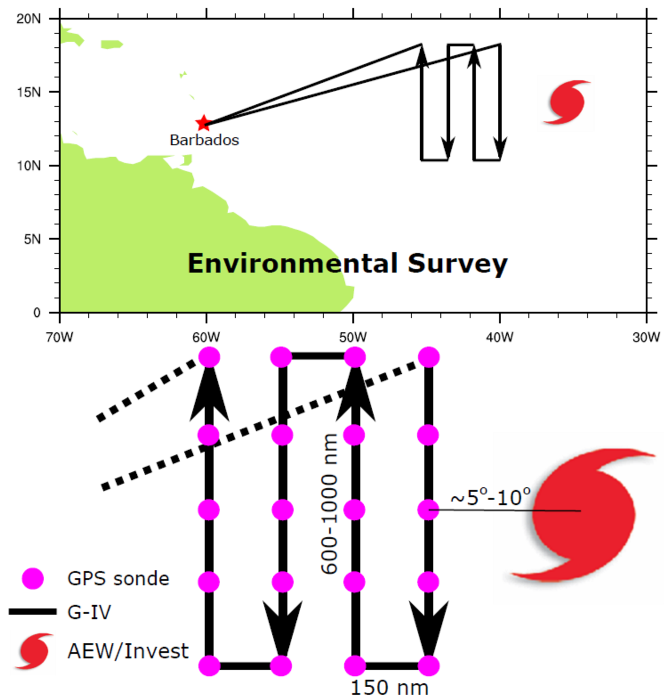


Figure GN-1. *Example lawnmower pattern to be flown (track in black) by the G-IV, dropsonde locations within the pattern (purple), and the relative location of the AEW/Invest center (hurricane symbol)*

EARLY STAGE EXPERIMENT
Pattern and Module Descriptions

Investigator(s): Rob Rogers, Jon Zawislak (Co-PIs), Ghassan Alaka, Jason Dunion, Heather Holbach, Trey Alvey (U. Utah), Josh Wadler (U. Miami/RSMAS) (Co-Is)

Requirements: TD, TS, Category 1

SCIENCE OBJECTIVE #1: *Collect datasets that can be used to improve the understanding of intensity change processes, as well as the initialization and evaluation of 3-D numerical models, particularly for TCs experiencing moderate vertical wind shear*
[Analysis of Intensity Change Processes Experiment, AIPEX]

P-3 Pattern #1: AIPEX

What to Target: Sample the inner core region of a TC

When to Target: Every 12 h [*optimal*] or every 24 h [*minimal*], preferably in coordination with a corresponding G-IV mission (**G-IV Pattern #1: AIPEX** or **G-IV Pattern #2: AIPEX**)

Pattern: Standard Rotated Figure-4

Flight altitude: [*optimal*] 10–12 kft (5 kft is minimum altitude for dropsonde launches)

Leg length or radii: 105 n mi

Estimated in-pattern flight duration: ~ 5 h

Expendable distribution: [*optimal*] (up to 28 dropsondes total) Modify standard by moving the mid-point dropsonde to half the radius of innermost G-IV radii. AXBTs preferably paired with dropsondes at mid- and turn points and center. If radius of maximum wind (RMW) is significantly different (> 10 n mi) from any of the standard dropsonde locations, release dropsonde there, and also release dropsonde at 1.5 x RMW, subject to same constraint regarding proximity to standard dropsonde locations. No AXBTs need to be coordinated with these RMW-based drops.

[*minimal*] (10–12 dropsondes total) Modify standard as stated in [*optimal*], keeping only midpoint drops, as well as center drops on the first and last pass. AXBTs preferably paired with dropsondes at midpoints and center.

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits. Inbound-outbound passes should be uninterrupted. DWL should be downward looking, 20° off nadir.

P-3 Pattern #2: AIPEX

What to Target: Sample the inner core and near environment regions of a TC when the *inner core precipitation distribution is asymmetric and when the G-IV is not available for coordination*

When to Target: Every 12 h [*optimal*] or every 24 h [*minimal*]

Pattern:

[*optimal*] P-3 Circumnavigation with Rotated Figure-4 (*modified* from the *standard*)

[*minimal*] P-3 Circumnavigation with single Figure-4 (*standard*)
Note: The circumnavigation can be adjusted for hazard avoidance; e.g., if pattern in downshear hemisphere is not possible, the circumnavigation can be abbreviated to the upshear hemisphere with a pass over the center (see example below in Fig. ES-1):

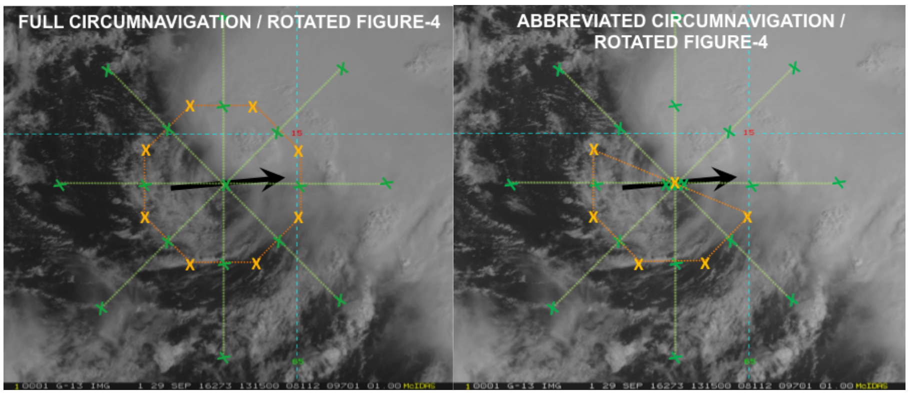


Figure ES-1. *Standard Rotated Figure-4 pattern dropsonde locations (green 'x') with full circumnavigation (orange 'x') (left panel), and with partial circumnavigation (right panel)*

Flight altitude: Figure-4: [*optimal*] 10–12 kft (5 kft is minimum altitude for dropsonde launches). Circumnavigation: As high as possible [*optimal*] above 25 kft [*minimal*]

Leg length or radii: 105 n mi (leg length). Radius of circumnavigation is preferably as close to the inner-core precipitation shield as safety allows.

Estimated in-pattern flight duration: [*optimal*] Circumnavigation with rotated Figure-4, ~6 h; [*minimal*] Circumnavigation with single Figure-4, ~ 4 h

Expendable distribution: [*optimal*] Use the standard for P-3 circumnavigation (8 dropsondes), as well as for rotated Figure-4 (20 dropsondes, 28 total with circumnavigation) or single Figure-4 (10 dropsondes, 18 total with circumnavigation). AXBTs preferably paired with dropsondes at mid- and turn points and center.

[*minimal*] Use the standard for P-3 circumnavigation (8 dropsondes), and modify standard Figure-4 by keeping only turn point drops, as well as center drops on the first and last pass (for rotated Figure-4, 10 dropsondes, 18 total with circumnavigation; for single Figure-4, 6 dropsondes, 14 total with circumnavigation). AXBTs preferably paired with dropsondes at turn points and center.

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits. Inbound-outbound passes should be uninterrupted. DWL should be downward looking, 20° off nadir.

EARLY STAGE EXPERIMENT
Pattern and Module Descriptions

G-IV Pattern #1: AIPEX

What to Target: Sample the environment and near environment of the TC

When to Target: Every 12 h [*optimal*] or every 24 h [*minimal*], preferably in coordination with a corresponding P-3 mission (**P-3 Pattern #1: AIPEX**)

Pattern: Standard G-IV Circumnavigation (octagon [*optimal*], hexagon [*minimal*]). Should be storm centered and oriented such that the left and right of shear semicircles are sampled equally by dropsondes.

Flight altitude: 40–45 kft

Leg length or radii: 200 n mi (370 km), 120 n mi (222 km), and 60 n mi (111 km) (radii**).** The innermost radii can be adjusted outward if necessitated by hazard avoidance (outer two radii rings should be similarly adjusted, if time allows).

Estimated in-pattern flight duration: ~ 5–6 h

Expendable distribution: Dropsonde at each turn point; 24 in total (octagon) [*optimal*], or 18 in total (hexagon) [*minimal*]

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits.

G-IV Pattern #2: AIPEX

What to Target: Sample the surrounding environment of the TC

When to Target: Every 12 h [*optimal*] or every 24 h [*minimal*]

Pattern: G-IV Star (with circumnavigation if no coordination with P-3)

Flight altitude: 40–45 kft

Leg length or radii: 210 n mi (388 km) outer, 90 n mi (167 km) inner radii (*standard*). Depending on the time of day, aircraft duration limitations, and safety considerations, the lengths of the inner (outer) points could be shortened (extended) if an opportunity to sample a diurnal pulse presents itself (see TC Diurnal Cycle Experiment).

Estimated in-pattern flight duration: ~ 4 h (~ 5 h with circumnavigation)

Expendable distribution: Dropsonde at each turn point; 13 dropsondes total (20 with circumnavigation)

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits.

EARLY STAGE EXPERIMENT
Pattern and Module Descriptions

SCIENCE OBJECTIVE #2: *Obtain a quantitative description of the kinematic and thermodynamic structure and evolution of intense convective systems (convective bursts) and the nearby environment to examine their role in TC intensity change*
[Convective Burst Structure and Evolution Module, CBM]

P-3 Module #1: CBM

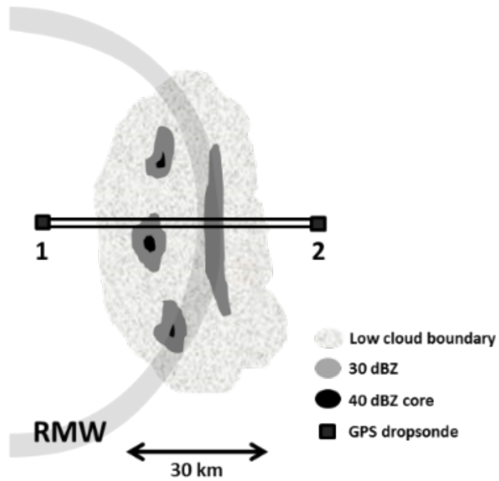
What to Target: An area of vigorous, deep convection occurring within the circulation of a tropical cyclone (TC)

When to Target: When deep convection is identified either by radar or satellite during the execution of a survey pattern at or near the radius of maximum wind (RMW) of a tropical depression, tropical storm, or Category 1 hurricane. Particular attention should be paid when a developing area of deep convection can be detected on the downshear (shear direction inferred by real-time SHIPS analyses) side of the storm.

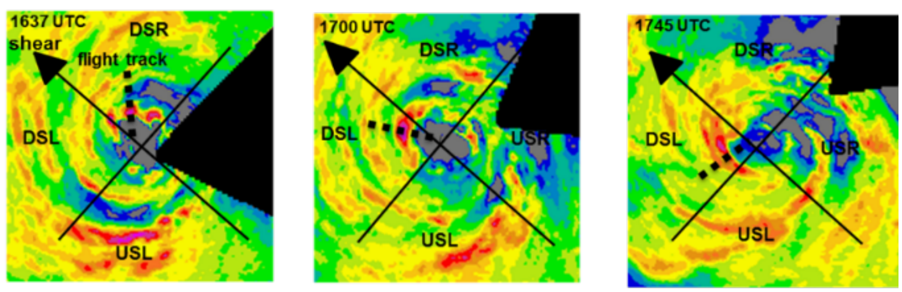
Pattern: Series of inbound/outbound radial penetrations / bowtie pattern (Fig. ES-2)

Repeated sampling can allow for a following of the burst around the storm, or if the burst remains confined downshear.

- Repeat penetrations as long as time permits within the 1–2 h window
- When a high-altitude aircraft is present, efforts should be made to coordinate the pattern with the high-altitude aircraft, so that the two aircraft are as close to vertically stacked as possible.



(a)



(b)

Figure ES-2. *P-3 Convective burst module: (a) Radial penetrations / bowtie pattern. Black square denote locations of GPS dropsondes from P-3. This pattern should be repeated multiple times as time allows, following the CB around the storm or remains confined downshear. (b) Example of sampling strategy following CBs around the storm, beginning downshear right (DSR) and into the upshear quadrants. Each radial pass is separated by ~30 minutes.*

Flight altitude: A constant altitude of 10–12 kft (radar or pressure altitude) is preferable

Leg length or radii: Variable depending on size of CB, but should extend at least 10 n mi inside and 10 n mi outside radar-defined edges of CB

Estimated in-pattern flight duration: ~1–2 h added to the mission

Expendable distribution: Dropsondes at turn points. No more than 15 dropsondes needed for this module. No AXBTs required.

Instrumentation Notes: Every effort made to fly the aircraft level for optimal Doppler radar sampling

EARLY STAGE EXPERIMENT
Pattern and Module Descriptions

SCIENCE OBJECTIVE #3: *Improve our understanding of the physical processes responsible for the formation and evolution of arc clouds, as well as their impacts on TC structure and intensity in the short-term* (Arc Cloud Module)

P-3 Module #1: Arc Cloud

What to Target: Large arc cloud features (100's of km in length) emanating from the periphery of TCs

When to Target: There are optimal times of day when large arc clouds occur and therefore preferred times of day for conducting this module. Arc clouds are linked to the position of radially propagating TC diurnal pulses that pass through areas of dry mid-level air (≤ 45 mm Total Precipitable Water [TPW]) and therefore will tend to occur from ~0400–1200 LST in the approximate radial operating area of the P-3.

Pattern: Transect orthogonal to the radially propagating arc cloud

Flight altitude: 10–12 kft, or as high as possible to provide better vertical sampling of arc clouds by GPS dropsondes that are deployed

Leg length or radii: Variable depending on the location of the arc cloud, but a transect through the arc cloud should be made that spans from the convective area where the arc cloud originated to at least 20 km beyond the leading edge of the arc cloud.

Estimated in-pattern flight duration: ~30–60 min added to the mission

Expendable distribution: GPS dropsonde spacing should be ~10 n mi (20 km) [reduced to ~5 n mi (~10 km) spacing closer (10 n mi [20 km]) to the arc cloud] and the transect can be made inbound (sampling in front of, across, and behind the arc cloud) or outbound (sampling behind, across, and then ahead of the arc cloud) relative to the convective core region of the AEW/TC.

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits.

G-IV Module #1: Arc Cloud

What to Target: Large arc cloud features (100's of km in length) emanating from the periphery of TCs

When to Target: There are optimal times of day when large arc clouds occur and therefore preferred times of day for conducting this module. Arc clouds are linked to the position of radially propagating TC diurnal pulses that pass through areas of dry mid-level air (≤ 45 mm TPW) and therefore will tend to occur from ~0400–1500 LST in the approximate radial operating area of the G-IV.

Pattern: Arc cloud transect

Flight altitude: 41–45 kft, or as high as possible to provide better vertical sampling of arc clouds by GPS dropsondes that are deployed

Leg length or radii: Variable depending on the location of the arc cloud, but a transect through the arc cloud should be made that spans from the convective area where the arc cloud originated to at least 30 n mi (50 km) beyond the leading edge of the arc cloud.

Estimated in-pattern flight duration: ~30 min added to the mission

Expendable distribution: GPS dropsonde spacing should be ~20 n mi (~35 km) and the transect can be made inbound (sampling in front of, across, and behind the arc cloud) or outbound (sampling behind, across, and then ahead of the arc cloud) relative to the convective core region of the AEW/TC.

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits.

MATURE STAGE EXPERIMENT
Pattern and Module Descriptions

Investigator(s): Paul Reasor, Jason Dunion (Co-PIs), Sim Aberson, Hui Christophersen, Paul Chang, Joe Cione, John Gamache, Heather Holbach, Ghassan Alaka, Kelly Ryan, Paul Leighton, Robert Rogers, Zorana Jelenak, Jun Zhang (Co-Is)

Requirements: Categories 2–5

SCIENCE OBJECTIVE #1: *Collect observations targeted at better understanding internal processes contributing to mature hurricane structure and intensity change. These processes include mixing between the eye and eyewall, secondary eyewall formation, the TC diurnal cycle, and gravity waves that emanate from the TC inner core*
[Internal Processes]

TC DIURNAL CYCLE

P-3 Pattern #1: Internal Processes (TC Diurnal Cycle)

What to Target: Sample the inner core and near environments of the TC

When to Target: Any strength TC (though TC diurnal cycle signals tend to be stronger in Cat 2+ storms); no land restrictions. There are time restrictions for this experiment: in-storm sampling should occur in the time window from ~0200–1200 LST during the early stages of the TC diurnal cycle when the TC diurnal pulse is located at radius, R≤300 km (R≤160 n mi). Approximate radial locations of TC diurnal pulses relative to local time are shown by the TC diurnal clock (see Figure MA-1 in the Mature Stage Science Description). If possible, this P-3 pattern should be conducted in coordination with **G-IV Pattern #1: Internal Processes (TC Diurnal Cycle)**.

Pattern: Any standard P-3 pattern that provides symmetric coverage (e.g. Rotated Figure-4, Figure-4 Butterfly, etc.). Leg lengths should be adjusted as needed to ensure that the aircraft perpendicularly crosses TC diurnal pulses that are indicated by satellite imagery and/or the P-3 LF radar.

Flight altitude: 10–12 kft, or as high as possible to provide better vertical sampling by GPS dropsondes that are deployed.

Leg length or radii: Standard leg lengths (105 n mi), but legs should be extended as needed to ensure that the aircraft perpendicularly crosses TC diurnal pulses that are indicated by satellite imagery and/or the P-3 LF radar.

Estimated in-pattern flight duration: ~2.5–5.0 hr

Expendable distribution: Standard distribution of GPS dropsondes except increased density of ~15–20 n mi (30–35 km) spacing just ahead of, within, and behind the diurnal pulse convective features that will be identified in real-time using satellite imagery and/or the P-3 LF radar (10–25 GPS dropsondes total). AXBTs are not a mission requirement.

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits.

MATURE STAGE EXPERIMENT
Pattern and Module Descriptions

G-IV Pattern #1: Internal Processes (TC Diurnal Cycle)

What to Target: Sample the inner core and near environments of the TC

When to Target: Any strength TC (though TC diurnal cycle signals tend to be stronger in Cat2+ storms); no land restrictions. There are time restrictions for this experiment: in-storm sampling should occur in the time window from approximately 0800–1500 LST during the middle to late stages of the TC diurnal cycle when the TC diurnal pulse is located between radius, R~200–400 km (~105–215 n mi). If possible, this G-IV pattern should be conducted in coordination with **P-3 Pattern #1: Internal Processes (TC Diurnal Cycle)**.

Pattern: Standard G-IV Star with Circumnavigation [*optimal*] or Star [*minimal*] pattern. Leg lengths should be adjusted as needed to ensure that the aircraft perpendicularly crosses TC diurnal pulses that are indicated by satellite imagery and/or the P-3 LF radar (if available).

Flight altitude: 41–45 kft, or as high as possible to provide better vertical sampling by GPS dropsondes that are deployed.

Leg length or radii: 190–215 n mi (350–400 km) for the outer points and ~60–90 n mi (110–165 km) for the inner points. If a circumnavigation is being performed, a constant radius [typically 60–90 n mi (110–165 km)] should be selected. Selection of the inner points and circumnavigation radii should be as close to the edge of the inner core convection as possible (this distance will be dictated by safety considerations) and will require coordination between the HRD LPS and the G-IV Flight Director.

Estimated in-pattern flight duration: ~4 hr without circumnavigation and ~5.25 hr with circumnavigation

Expendable distribution: Standard plus mid-points of star pattern (25–31 GPS dropsondes total) except increased density of ~15–20 n mi (30–35 km) spacing just ahead of, within, and behind the diurnal pulse convective features that will be identified in real-time using satellite imagery and/or the P-3 LF radar.

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits.

GRAVITY WAVE

P-3 Module #1: Internal Processes (Gravity Wave)

What to Target: Sample the inner core and near environments of the TC

When to Target: Any strength TC; no land restrictions. This module ideally should be conducted in quadrant with the least rainband activity, typically the upshear right or right-real quadrant. The best opportunity is at the end of a standard Figure-4 pattern, when the last leg terminates in a quadrant with less rainbands

Pattern: Any standard P-3 pattern that provides symmetric coverage (e.g. Rotated Figure-4, Figure-4 Butterfly, etc.). At the end of the last leg, continue outward to distance of 160 n mi from the center, or further if possible (see Fig. MA-1). Then turn the P-3 around and head directly back to the eye, retracing the previous leg in the opposite direction.

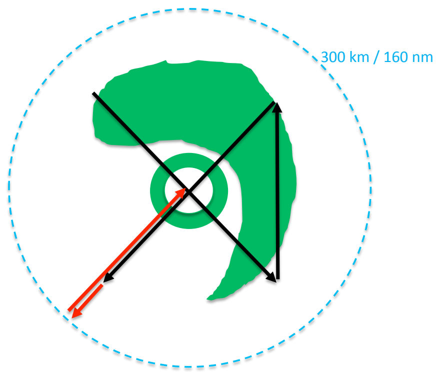


Figure MA-1. *Depiction of the Gravity Wave module in which the P-3 flies an extended leg (160 n mi) (red path) and reverses course along the same azimuth back to the eye*

Flight altitude: 10–12 kft or as high as possible

Leg length or radii: Leg lengths should extend to at least 160 n mi from the center, or further if time permits, including the turn leg back the center

Estimated in-pattern flight duration: ~40 min – 1 hr

Expendable distribution: Dropsonde and AXBTs are not a requirement

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits.

SECONDARY EYEWALL FORMATION (SEF)

P-3 Module #2: Internal Processes (Pre-SEF)

What to Target: Mature hurricane that has pronounced rainband activity, and possibly a secondary eyewall forming. We are targeting the inside edge of primary rainband and the overall primary rainband.

When to Target: Proposed flight pattern (Fig. MA-2) should take place when microwave satellite imagery indicates the presence of asymmetric rainbands occurring in the storm environment.

Pattern: Fly a combination of a Rotated Figure-4 and a rainband spiral along the inside edge of the rainband, within ~5–10 n mi of the inner edge of the rainband. Fly the spiral pattern straight and level as long as possible, i.e., keeping aircraft bank angle at a minimum, to minimize loss of radar data due to aircraft banking. Ferry time may preclude the second Figure-4.

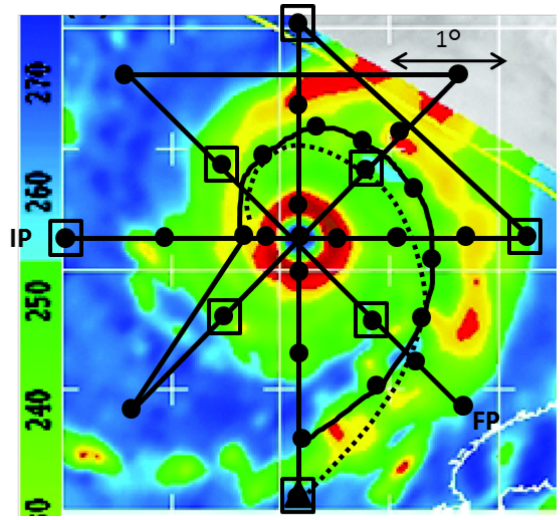


Figure MA-2. *Proposed flight pattern for pre-SEF with the P-3 that includes an initial Figure-4, and a track paralleling the primary rainband*

Flight Altitude: 10–12 kft preferable

Leg length or radii: The flight leg or radii depends on the primary rainband location. Ideally, the extension of the leg should be just outside of the primary rainband as indicated by Fig. MA-2.

Expendable distribution: For P-3, deploy dropsondes at all turn and mid-points in Figure-4, plus first center pass, at four locations in primary eyewall, and in the middle of rainband precipitation feature. Also release dropsonde at ~50 n mi spacing along rainband spiral. If Coyote is available, deploy it following the inflow path where it will collect observations that can be used to calculate boundary layer characteristics outside, within, and inside rainband.

Instrumentation Notes: N/A

P-3 Module #3: Internal Processes (Post-SEF)

What to Target: Mature hurricanes that are expected to have a secondary eyewall already formed or are undergoing an ERC. We are targeting the concentric rings and the moat region.

When to Target: These concentric rings can be easily detected based on radar or microwave satellite imagery. For storms that are already undergoing these ERCs and repeated ERCs are forecast, sampling patterns as indicated in Fig. MA-3 are proposed.

Pattern: Fly a combination of a Rotated Figure-4 and a circumnavigation in the moat region, within ~5–10 n mi of the inner edge of the outer eyewall (see Fig. MA-3). Fly the circumnavigation straight and level as long as possible, i.e., keeping aircraft bank angle at a minimum, to minimize loss of radar data due to aircraft banking. Ferry time may preclude the second Figure-4.

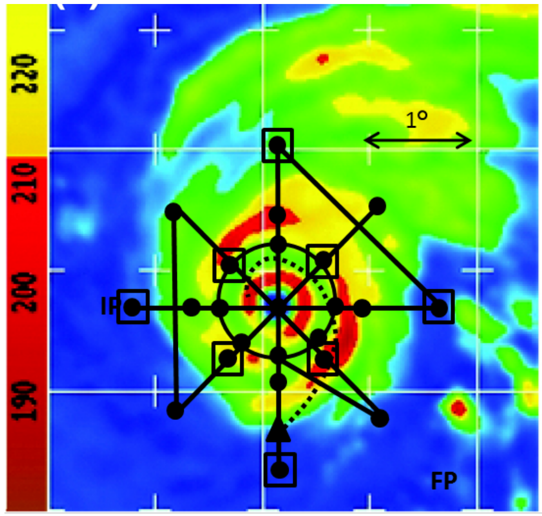


Figure MA-3. *Proposed flight pattern for post-SEF with the P-3 that includes an initial Rotated Figure-4 and a follow-on circumnavigation of the moat region*

Flight Altitude: 10–12 kft preferable

Leg length or radii: The flight leg or radii depends on the primary rainband location. Ideally, the extension of the leg should be just outside of the primary rainband as indicated by Fig. MA-3 and the circumnavigation is inside the moat region.

Expendable distribution: Deploy dropsondes at all turn and mid-points in Rotated Figure-4 survey pattern, plus first center pass, at four locations in primary eyewall. Also release dropsonde at ~50 n mi spacing along circumnavigation in moat region. If Coyote is available, deploy it following the inflow path where it will collect observations that can be used to calculate boundary layer characteristics outside, within, and inside outer eyewall.

Instrumentation Notes: Preferably fly DWL for the circumnavigation, maintaining straight legs as best as possible while executing circumnavigation

G-IV Module #1: Internal Processes (SEF)

What to target: Sample the environment of a TC right outside of the primary rainband

When to target: Proposed flight pattern should take place when microwave satellite imagery indicates the presence of asymmetric rainbands occurring in the storm environment when there is a high chance the storm may undergo SEF. In the case that the ERC is already occurring, these concentric rings can be easily detected based on radar or microwave satellite imagery. Fly the circumnavigation patterns outside of the outer rainband.

Pattern: G-IV Circumnavigation; fly pattern such that the innermost circumnavigation (octagon or hexagon) is as close to outer edge of rainband as is safely allowed. Standard circumnavigation (octagon or hexagon) would work as long as the inner radius is close to outer edge of the rainband.

Flight altitude: 41–45 kft preferable

Leg length or radii: The flight leg or radii depends on the primary rainband location. The innermost radius should be as close to the outer edge of the rainband as is safely allowed.

Expendable distribution: Deploy dropsondes at all turn points. The octagons are all turn points could also be staggered rather than aligned to achieve better azimuthal sonde coverage.

Instrumentation Notes: N/A

EYE-EYEWALL MIXING

P-3 Module #4: Internal Processes (Eye-Eyewall Mixing)

What to Target: This module requires a TC with a clearly defined, visible eye, eyewall, and inversion and an eye diameter of at least 25 n mi.

When to Target: The module should only be attempted during daytime missions. It can be included within any missions during aircraft passage through the eye.

Pattern: This is a break-away pattern that is compatible with any standard pattern with an eye passage (all P-3 patterns except the Square spiral or Lawnmower). The P-3 will penetrate the eyewall at the standard-pattern altitude. Once inside the eye, the P-3 will descend to a safe altitude below the inversion while performing a Figure-4 pattern (Fig. MA-4). The leg lengths will be determined by the eye diameter, with the ends of the legs at least 2 n mi from the edge of the eyewall. Upon completion of the descent, the P-3 will circumnavigate the eye about 2 n mi from the edge of the eyewall in the shape of a pentagon or hexagon (Fig. MA-4). Time permitting; another Figure-4 will be performed during ascent to the original flight level. Depending upon the size of the eye, this pattern should take between 0.5 and 1 h.

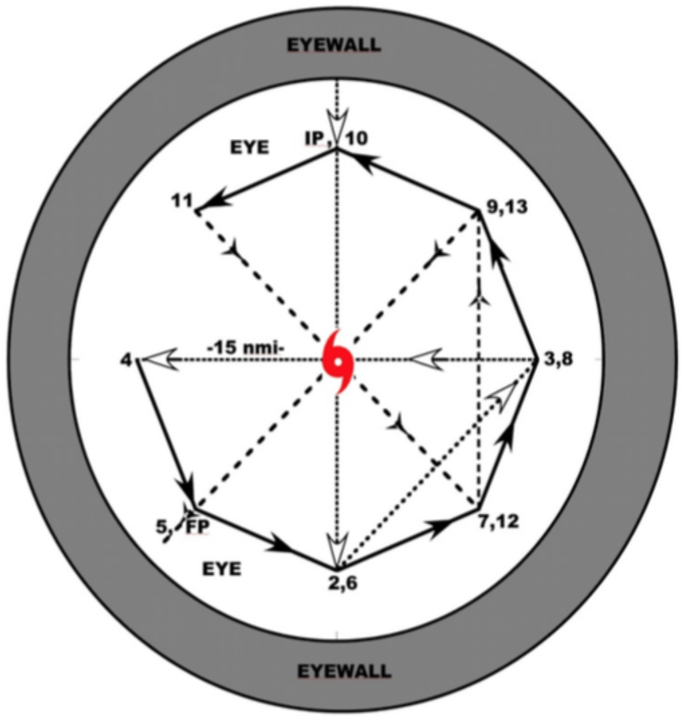


Figure MA-4. *Depiction of the eye-eyewall mixing module*

Flight altitude: The flight altitude will vary from just below the inversion inside the eye to the standard-pattern altitude.

Leg length or radii: The leg lengths will be determined by the eye diameter, with the ends of the legs at least 2 n mi from the edge of the eyewall. Upon completion of the descent, the P-3 will circumnavigate the eye about 2 n mi from the edge of the eyewall in the shape of a pentagon or hexagon.

Estimated in-pattern flight duration Depending upon the size of the eye, this pattern should take between 0.5 and 1 h.

Expendable distribution: No expendables required

Instrumentation Notes: No special instructions for operation. If DWL is available, it should scan downward, though not exclusively, during the pattern. Each leg of the pattern should be straight within safety constraints.

MATURE STAGE EXPERIMENT
Pattern and Module Descriptions

SCIENCE OBJECTIVE #2: *Collect observations targeted at better understanding the response of mature hurricanes to their changing environment, including changes in vertical wind shear and underlying oceanic conditions* [Environment Interaction]

TC IN SHEAR

P-3 Pattern #1: Environment Interaction (TC in Shear)

What to Target: Sample the *core region* of a TC for which the distance of the center from significant land mass and significant SST gradients exceeds ~ 3x the radius of maximum wind.

When to Target: Sample before a significant increase in environmental vertical wind shear. The P-3 should be coordinated with **G-IV Pattern #1: Environment Interaction (TC in Shear)**.

Pattern: Rotated Figure-4. Alternate patterns: Butterfly; Fig-4; Alpha

Flight altitude: 12 kft preferable for best dropsonde coverage

Leg length or radii: 105 n mi

Estimated in-pattern flight duration: ~ 5 h

Expendable distribution: Modify standard by including an RMW dropsonde, moving the mid-point dropsonde to half the radius of innermost G-IV circumnavigation (or 30 n mi) and removing turn-point dropsondes. Modification ensures eyewall thermodynamic coverage and 30 n mi radial sampling of thermodynamic fields immediately outside the eyewall. Modification also leverages availability of G-IV dropsondes (20 dropsondes total).

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits. Inbound-outbound passes should be uninterrupted.

P-3 Pattern #2: Environment Interaction (TC in Shear)

What to Target: Sample the *core region* of a TC for which the distance of the center from significant land mass and significant SST gradients exceeds ~ 3x the radius of maximum wind.

When to Target: Sample as the large-scale, deep-layer shear increases and downshear convective asymmetry is evident; when the TC core exhibits large vertical tilt (an intensifying TC may have reduced its rate of intensification or begun to weaken); and when the TC core has realigned (a weakening or steady state TC may have begun to intensify).

Pattern: Figure-4, fly 45 deg downwind, then uninterrupted small-scale Rotated Figure-4. Orient initial pass along shear vector if possible. Purpose of small-scale Rotated Figure-4 is high-temporal-resolution sampling of eyewall and near-eyewall thermodynamic structure. Alternate (small-scale) patterns: Butterfly for coarser azimuthal sampling; P-3 Circumnavigation

Flight altitude: 12 kft preferable for best dropsonde coverage

Leg length or radii: 105 n mi (initial Figure-4); small-scale Rotated Figure-4 should extend just beyond the primary region of organized convection outside the eyewall (~15–30 n mi beyond *mean* radius of maximum wind).

Estimated in-pattern flight duration: ~ 4 h 45 min for Figure-4 + Rotated Figure-4 (45 n mi legs)

Expendable distribution: For initial Figure-4, modify standard by removing mid-point dropsondes (if G-IV present, remove IP and turn-point dropsondes). For small-scale Rotated Figure-4, modify standard by launching 4 equally-spaced dropsondes from the *mean* radius of maximum wind to the turn point of each leg (42 dropsondes total, 38 if G-IV present). Given limited resources, may target only quadrant *downwind* of organized convection (22 dropsondes total, 18 if G-IV present).

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits. Inbound-outbound passes should be uninterrupted.

G-IV Pattern #1: Environment Interaction (TC in Shear)

What to Target: Sample the *environment* of a TC for which the distance of the center from significant land mass and significant SST gradients exceeds ~ 3x the radius of maximum wind.

When to Target: Sample before a significant increase in environmental vertical wind shear; during the period of maximum vortex tilt. Coordinate G-IV takeoff with the corresponding P-3 mission such that the innermost G-IV circumnavigation coincides with the P-3 sampling.

Pattern: G-IV Circumnavigation (Hexagon). Should be storm centered. Alternate patterns: G-IV Circumnavigation (Octagon) for more sondes; G-IV Star if TDR coverage is not crucial

Flight altitude: 41–45 kft

Leg length or radii: 150 n mi, 90 n mi, and 60 n mi

Estimated in-pattern flight duration: ~ 4 h 25 min

Expendable distribution: Standard (18 dropsondes total).

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits.

ARC CLOUD

P-3 Module #1: Environment Interaction (Arc Cloud)

What to Target: Large arc cloud features (100's of km in length) emanating from the periphery of TCs

When to Target: There are optimal times of day when large arc clouds occur and therefore preferred times of day for conducting this module. Arc clouds are linked to the position of radially propagating TC diurnal pulses that pass through areas of dry mid-level air (≤45 mm Total Precipitable Water

[TPW]) and therefore will tend to occur from ~0400–1200 LST in the approximate radial operating area of the P-3.

Pattern: Transect orthogonal to the radially propagating arc cloud

Flight altitude: 10–12 kft, or as high as possible to provide better vertical sampling of arc clouds by GPS dropsondes that are deployed

Leg length or radii: Variable depending on the location of the arc cloud, but a transect through the arc cloud should be made that spans from the convective area where the arc cloud originated to at least 20 km beyond the leading edge of the arc cloud.

Estimated in-pattern flight duration: ~30–60 min added to the mission

Expendable distribution: GPS dropsonde spacing should be ~10 n mi (20 km) [reduced to ~5 n mi (~10 km) spacing closer (10 n mi [20 km]) to the arc cloud] and the transect can be made inbound (sampling in front of, across, and behind the arc cloud) or outbound (sampling behind, across, and then ahead of the arc cloud) relative to the convective core region of the AEW/TC.

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits.

G-IV Module #1: Environment Interaction (Arc Cloud)

What to Target: Large arc cloud features (100's of km in length) emanating from the periphery of TCs.

When to Target: There are optimal times of day when large arc clouds occur and therefore preferred times of day for conducting this module. Arc clouds are linked to the position of radially propagating TC diurnal pulses that pass through areas of dry mid-level air (≤45 mm TPW) and therefore will tend to occur from ~0400–1500 LST in the approximate radial operating area of the G-IV.

Pattern: Arc cloud transect

Flight altitude: 41–45 kft, or as high as possible to provide better vertical sampling of arc clouds by GPS dropsondes that are deployed

Leg length or radii: Variable depending on the location of the arc cloud, but a transect through the arc cloud should be made that spans from the convective area where the arc cloud originated to at least 30 n mi (50 km) beyond the leading edge of the arc cloud.

Estimated in-pattern flight duration: ~30 min added to the mission

Expendable distribution: GPS dropsonde spacing should be ~20 n mi (~35 km) and the transect can be made inbound (sampling in front of, across, and behind the arc cloud) or outbound (sampling behind, across, and then ahead of the arc cloud) relative to the convective core region of the AEW/TC.

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits.

MATURE STAGE EXPERIMENT
Pattern and Module Descriptions

SCIENCE OBJECTIVE #3: *Test new (or improved) technologies with the potential to fill gaps, both spatially and temporally, in the existing suite of airborne measurements in mature hurricanes. These measurements include improved three-dimensional representation of the hurricane wind field, more spatially dense thermodynamic sampling of the boundary layer, and more accurate measurements of ocean surface winds*
[New Observing Systems (NOS)]

COYOTE

P-3 Module #1: NOS (Coyote, Eyewall A)

What to Target: Sample the *core region* of a mature TC

When to Target: After the hurricane eye is formed

Pattern: "Sun Pattern" with varying orientation and number of "rays" (Fig. MA-5) or "Pizza Slice" pattern with varying orientation and number of "slices" (see Fig. MA-6). Orientation will be determined by characteristics of the hurricane.

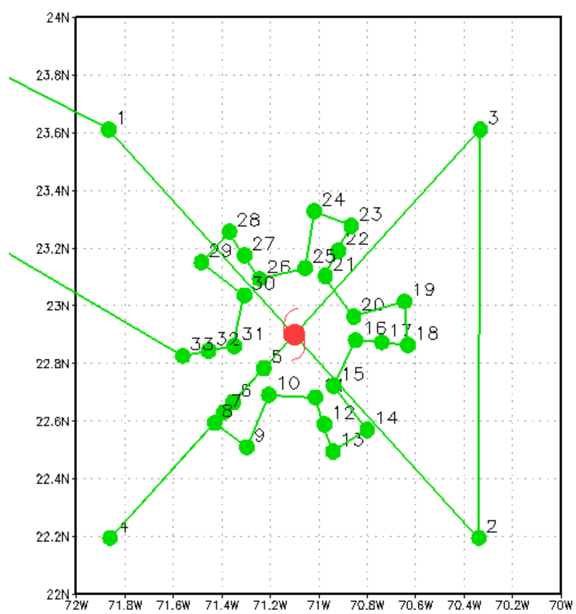


Figure MA-5. *Example "sun pattern"*

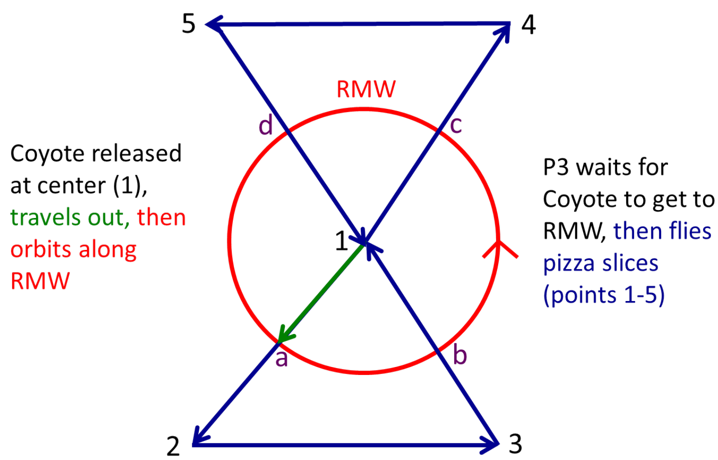


Figure MA-6. *Example "pizza slice" pattern*

Flight altitude: 10–12 kft

Leg length or radii: Will depend on radius of maximum wind (RMW) and estimated wind-speed intensity (longest legs such that Coyote-P-3 communication is maintained)

Estimated in-pattern flight duration: ~ 1 h

Expendable distribution: The Coyote UAS will be dropped in the eye and directed at an orientation determined by the characteristics of the hurricane. 1 center sonde and 2 sondes per ray/slice are required for this module (i.e. a total of 13 sondes for a 3 ray/slice pattern). Dropsondes will be deployed along the RMW such that they fall within 10 km of the Coyote at the given time (but no closer than 5 km). For this module, IR sondes are used at outer and inner portions of each ray/slice and for the center drop. If available, AXBTs will accompany outer IR sondes.

Instrumentation Notes: Use straight flight legs as safety permits.

P-3 Module #2: NOS (Coyote, Eyewall B)

What to Target: Sample the azimuthal location of the maximum wind (Vmax) of a mature TC *after* a P-3 Figure-4 is complete and provides sufficient TDR coverage of the RMW

When to Target: After the hurricane eye is formed and after Vmax azimuth is identified

Pattern: "Sun Pattern" with 2nd or 3rd leg oriented along the same azimuth as Vmax and a varying number of "rays" (Fig. MA-5) or "Pizza Slice" pattern with 1st or 2nd leg oriented along the same azimuth as Vmax and a varying number of "slices" (see Fig. MA-6). Variation of P-3 Pattern 1; see **Figure 3** for additional sondes. Orientation will be determined by characteristics of the hurricane.

Flight altitude: 10–12 kft

Leg length or radii: Will depend on radius of maximum wind (RMW) and estimated RMW wind-speed (longest legs such that Coyote-P-3 communication is maintained)

Estimated in-pattern flight duration: ~ 1 h

Expendable distribution: The Coyote UAS will be dropped in the eye and will be directed at an azimuth larger than that of Vmax. This first azimuth will be determined by the estimated hurricane wind speed and will allow the Coyote to reach the azimuth of Vmax at ~20 minutes into the module. 1 center sonde and 2 sondes per ray/slice are required for this module (i.e. a total of 13 sondes for a 3 ray/slice pattern) in addition to 6 sondes deployed on either side of the RMW during inbound/outbound legs along the Vmax azimuth. RMW sondes will be deployed along the RMW such that they fall within 10 km of the Coyote at the given time (but no closer than 5 km). For this module, IR sondes are used at outer and inner portions of each ray/slice and for the center drop. If available, AXBTs will accompany outer IR sondes.

Instrumentation Notes: Use straight flight legs as safety permits

P-3 Module #3: NOS (Coyote, Inflow)

What to Target: Sample the *inflow layer* of a TC

When to Target: No constraint

Pattern: Lawnmower pattern; number of legs determined by estimated hurricane RMW and wind speed

Flight altitude: 10–12 kft

Leg length or radii: Determined by estimated speed of inflow (longest legs such that Coyote-P-3 communication is maintained)

Estimated in-pattern flight duration: ~ 1 h

Expendable distribution: 1 sonde during each P-3-Coyote path intersect such that they fall within 10 km of the Coyote at the given time (but no closer than 5 km) and at select turn points. A total of 8 drops are estimated, and IRsondes are preferred. Up to 3 AXBTs may be deployed as well (LPS discretion).

Instrumentation Notes: Use straight flight legs as safety permits

NESDIS OCEAN WINDS

P-3 Pattern #1: NOS (Ocean Winds)

What to Target: The highest-wind region of a TC

When to Target: The ideal ocean winds storm would typically be a developed hurricane (category 1 and above) where a large range of wind speeds and rain rates would be found. However, data collected within tropical depressions and tropical storms would still provide very useful observations of rain impacts.

Pattern: Start with a survey pattern (Figure-4 or Butterfly). Then execute a racetrack or Lawnmower pattern over a feature of interest such as a rain band or wind band. Constant bank circles of 10–30 degrees: inserted along flight legs where the desired environmental conditions were present (region of no rain and where we might expect the winds to be consistent over a range of about 6–10 miles, about the diameter of a circle). This would not be something we would want to do in a high gradient region where the conditions would change significantly while we did the circle.

Flight altitude: The sensitivity of the IWRAP system defines the preferred flight altitude to be below 10 kft to enable the system to still measure the ocean surface in the presence of rain conditions typical of tropical systems. With the Air Force typically flying at 10-kft pressure, we have typically ended up with an operating altitude of 7-kft radar.

Leg length or radii: Initial survey extends 20–50 n mi from the storm center. The actual distance would be dictated by the storm size and safety of flight considerations. The racetrack/Lawnmower legs are just long enough to cover the feature of interest.

Estimated in-pattern flight duration Typically 8–9 h for full-duration mission

Expendable distribution: Sondes dropped in high-wind regions

Instrumentation Notes: Operating at a constant radar altitude is desired to minimize changes in range and thus measurement footprint on the ground. Higher altitudes would limit the ability of IWRAP consistently see the surface during precipitation, but these altitudes would provide useful data, such as measurements through the melting layer, to study some of the broader scientific questions. Straight and level flight with a nominal pitch offset unique to each P-3 is desired during most flight legs.

END STAGE EXPERIMENT
Pattern and Module Descriptions

Investigator(s): Sim Aberson, John Kaplan (Co-PIs), Peter Dodge, Ghassan Alaka, Heather Holbach, Jun Zhang, and Jason Dunion (Co-Is)

Requirements: TC making landfall, undergoing rapid weakening, or extratropical transition

SCIENCE OBJECTIVE #1: *Collect observations targeted at better understanding changes TCs undergo at landfall. Objectives include validation of surface wind speed estimates and model forecasts, understanding factors that modulate intensity changes near and after landfall, and to understand processes that lead to tornadoes in outer rainbands.*
[Landfall]

P-3 Module #1: Landfall (Offshore Intense Convection)

What to Target: An intense rain band > 150 n mi from the center of either a tropical storm or hurricane that is forecast to make landfall along the U.S coastline

When to Target: This module should be performed within 12–24 h of the time of landfall

Pattern: Break-away/non-standard (see Fig. EN-1 and description below):

Fig. EN-1 shows a sample Offshore Intense Convection flight pattern near the Carolina coast. The P-3 should cross the target band ~20–25 km downwind of the intense convective cells and then proceed to ~25 km outside the rain band axis. The aircraft then turns upwind and proceeds along a straight track parallel to the band axis. When the P-3 is ~20–25 km upwind of the target cells, the aircraft turns and proceeds along a track orthogonal to the band axis until the P-3 is 25 km inside the rain band then turns downwind and flies parallel to the rain band axis.

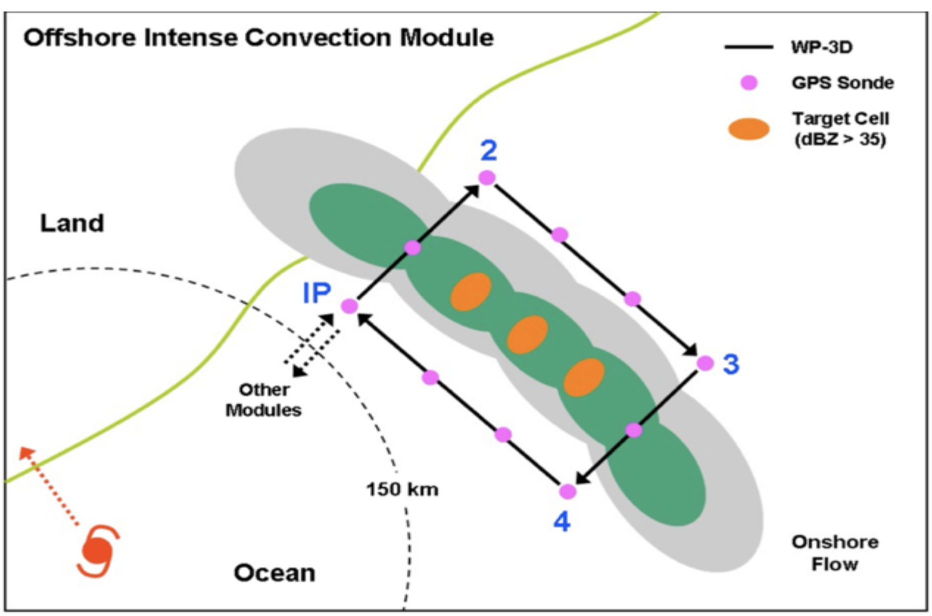


Figure EN-1. *Offshore Intense convection module*

Flight altitude: 10,000 ft (3000 m) or higher

Leg lengths: ≥ 75 km for each parallel leg

Estimated in-pattern flight duration: 1–2 h

Expendable distribution: Deploy dropwindsondes at the start or end points of each leg, at the band axis crossing points, and at ~20–25 km intervals along each leg parallel to the band. At least 2 dropwindsondes should be deployed on either side of the convection and at least 1 dropwindsonde should be deployed each time the band-axis is crossed (for a minimum of 6 dropwindsondes).

Instrumentation Notes: The Doppler radar should be turned on and scanning normally. Aircraft should avoid penetration of intense reflectivity regions (particularly over land).

P-3 Module #2: Landfall (Coastal Survey)

What to Target: A tropical storm or hurricane that is forecast to make landfall along the U.S coastline

When to Target: This module should be performed within ~6–12 h of the time of landfall

Pattern: Break-away/non-standard (see Fig. EN-2 below and description below):

Fig. EN-2 shows a sample Coastal Survey pattern for a hurricane landfall near Melbourne, Florida. The P-3 would fly parallel but ~10–15 km offshore so that the SFMR footprint is out of the surf zone. The second pass should be parallel and as close to the coast as safety permits. Finally, a short leg would be flown from the coast spiraling towards the storm center.

END STAGE EXPERIMENT
Pattern and Module Descriptions

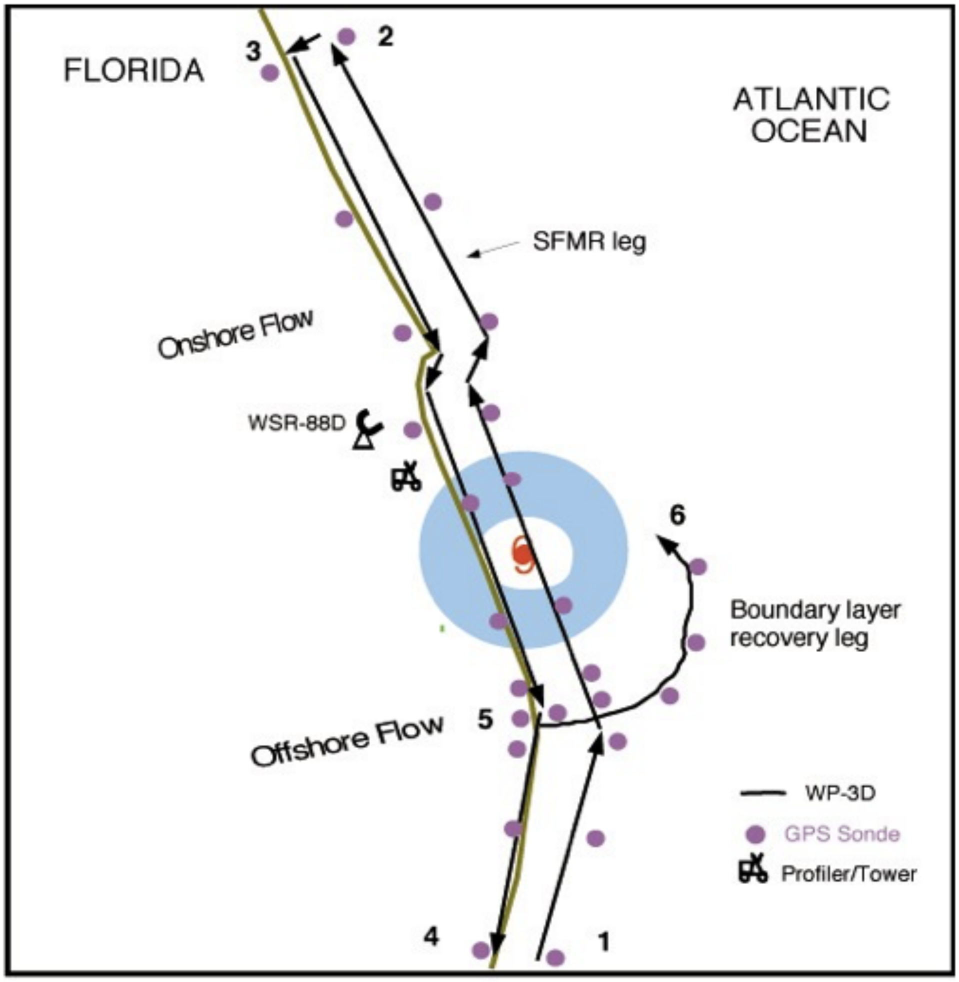


Figure EN-2. *Coastal Survey module*

Flight altitude: 5000 ft (1.5 km) for first pass and then climb to slightly higher altitude (~7,500 ft) if needed for second pass

Leg lengths: ~150 km

Estimated in-pattern flight duration: ~2 h

Expendable distribution: Dropwindsondes at RMW, and 12.5, 25, 50, 75, 100 km from RMW on either side of storm in both the near shore and offshore legs that are to be flown parallel to the shoreline. Dropwindsondes should be deployed quickly at start of outbound leg between near shore and offshore parallel legs and then every 10–15 km thereafter.

Instrumentation Notes: The Doppler radar should be turned on and scanning normally. Aircraft should avoid penetration of intense reflectivity regions (particularly those overland).

P-3 Module #3: Landfall (Real-time)

What to Target: A hurricane that is forecast to make landfall along the U.S coastline

When to Target: This module should be performed within ~6–12 h of the time of landfall

Pattern: Break-away/non-standard (see Fig. EN-3 and description below):

Fig. EN-3 shows a sample Real-time module flight pattern. The P-3 descends at the initial point and begins a low-level Figure-4 pattern, possibly modifying the legs to fly over buoy or C-MAN sites if possible. If time permits, the P-3 would make one more pass through the eye and then fly the Dual-Doppler option.

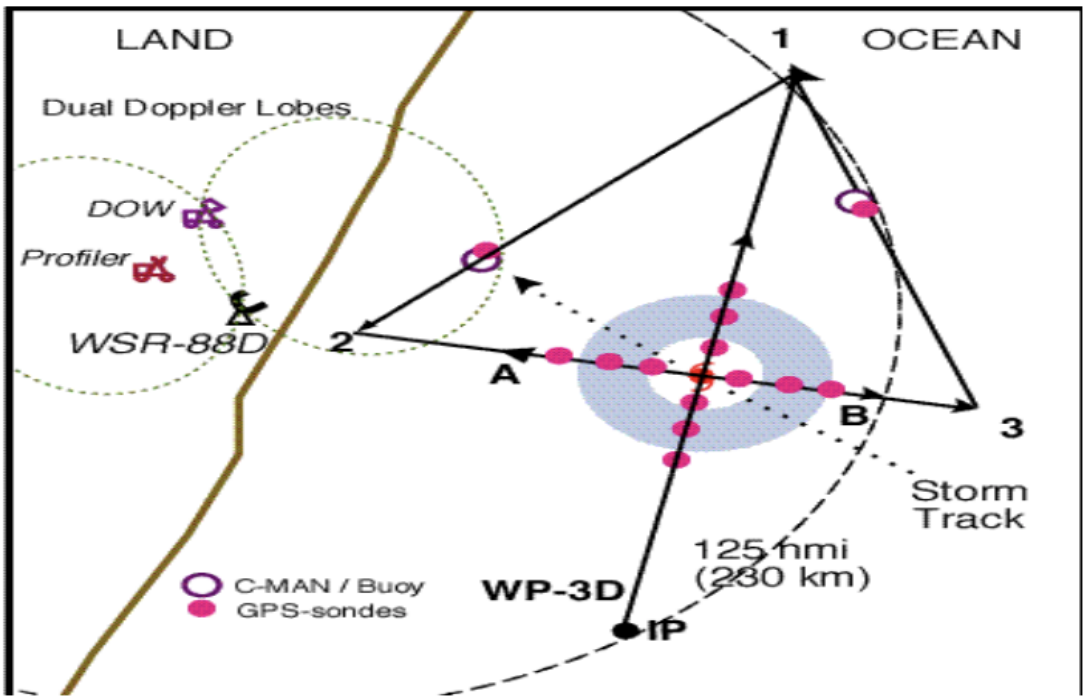


Figure EN-3. *Real-time module*

Flight altitude: Below 5,000 ft (1.5 km) (or the lowest level deemed to be safe by flight personnel)

Leg lengths: ~ 185 km

Estimated in-pattern flight duration: ~-2–3 h

Expendable distribution: Dropwindsondes should be released near buoys or C-MAN sites (if possible) and at or just inside the flight-level RMW

Instrumentation Notes: The Doppler radar should be turned on and scanning normally. Also, it is essential that these passes be flown as straight as possible, because turns to fix the eye will degrade the Doppler radar coverage.

P-3 Module #4: Landfall (SFMR Coastal)

What to Target: A tropical storm or hurricane that is forecast to make landfall in a region with varying bathymetry near the coastline

When to Target: This module should be performed when sustained winds are greater than 15 m s^{-1} in the region of interest

Pattern: Break-away/non-standard (see Fig. EN-4 and description below):

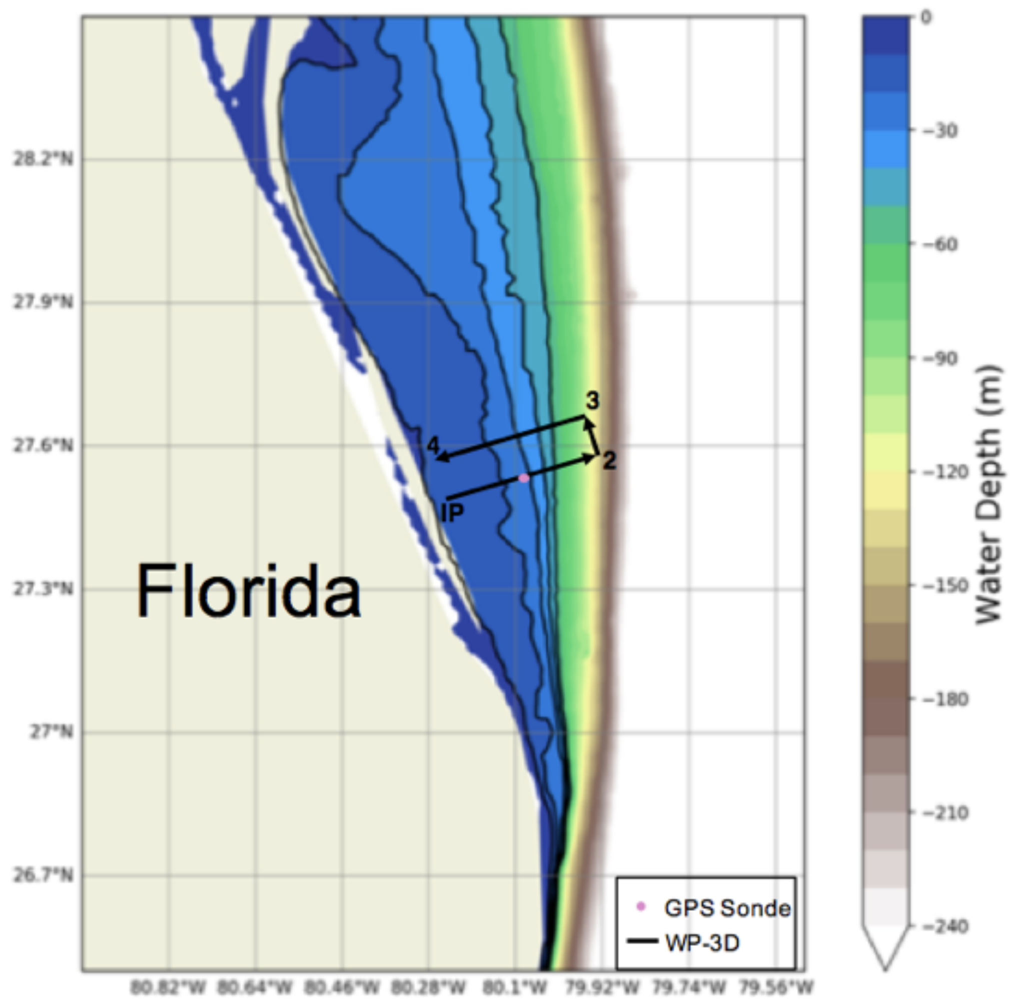


Figure EN-4. *SFMR coastal module*

The P-3 would fly perpendicular to the coastline, across the bathymetry gradient, in a region with near constant surface winds. After flying away from the coast for about 50 km, the P-3 would turn downwind and then back towards the coast repeating a similar line as the first leg.

Flight altitude: Can be performed at any altitude between 5,000 to 12,000 ft. Should maintain a constant altitude throughout the module.

Leg lengths: ~25–50 km

Estimated in-pattern flight duration: ~30–45 min

Expendable distribution: Dropwindsonde at middle of first leg. If winds appear to vary over the leg then an additional dropwindsonde may be necessary.

Instrumentation Notes: SFMR should be operating normally

END STAGE EXPERIMENT
Pattern and Module Descriptions

SCIENCE OBJECTIVE #2: *Collect observations targeted at better understanding changes TCs undergo while rapidly weakening over the open ocean or undergo extratropical transition.*
[Weakening/Extratropical Transition (ET)]

P-3 Pattern #1: Weakening/ET

What to Target: Two specific targets are to be sampled during each mission, the TC itself, and the interface between the TC and the environmental flow

When to Target: The systems will be sampled every 12 h from the time it begins the transition to an extratropical cyclone to the time it is out of range of the aircraft, or the system dissipates

Pattern: The patterns would likely be non-standard patterns. At least two passes through the center of the TC will be completed during the mission, though they need not be consecutive (Fig. EN-5). The P-3 will fly as high as possible to avoid hazards such as convective icing. Legs should be of equal length, except that they can be shortened to the south of the storm center if necessary to save time, or shortened due to land. If extra time is available, important interactions between the midlatitude jet stream and the outflow from the TC occur. This region will be investigated by releasing dropwindsondes every ~120 n mi during this part of the pattern.

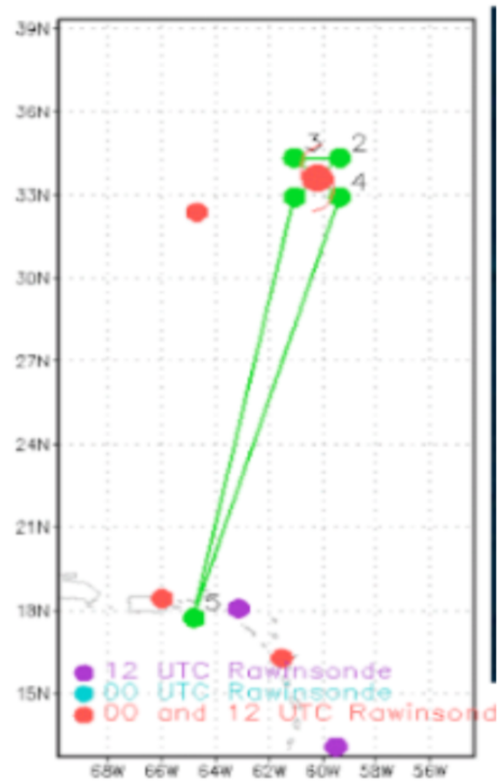


Figure EN-5. *Sample P-3 track investigating storm experiencing ET*

Flight altitude: As high as safely possible

Leg length or radii: Leg lengths depend on the size of the transitioning system. They should be of equal length, but can be shortened to the south, or due to land.

Estimated in-pattern flight duration: 8 h

Expendable distribution: 10 dropwindsondes, 10 AXBTs. During passes through the center, dropwindsondes will be deployed at each turn point and at evenly spaced intervals along each leg with optimal spacing near 90 n mi. AXBTs will be deployed at each turn point and at the midpoint of each leg only in the northern semicircle from the cyclone center.

Instrumentation Notes: Due to a trapped-fetch phenomenon, the ocean surface wave heights can reach extreme levels ahead of a TC undergoing ET. Therefore, primary importance for the P-3 in the northeast quadrant of the TC will be the scanning radar altimeter (WSRA) to observe the ocean surface wave spectra, if available. Flight level will be chosen to accommodate this instrument.

END STAGE EXPERIMENT
Pattern and Module Descriptions

G-IV Pattern #1: Weakening/ET

What to Target: Two specific targets are to be sampled during each mission, the TC itself, and the interface between the TC and the environmental flow

When to Target: The systems will be sampled every 12 h from the time it begins the transition to an extratropical cyclone to the time it is out of range of the aircraft, or the system dissipates

Pattern: The patterns would likely be non-standard patterns. At least two passes through the center of the TC will be completed during the mission (Fig. EN-6), though they need not be consecutive. Legs should be of equal length, except that they can be shortened to the south of the storm center if necessary to save time, or shortened due to land. Ahead of the TC, important interactions between the midlatitude jet stream and the outflow from the TC occur.

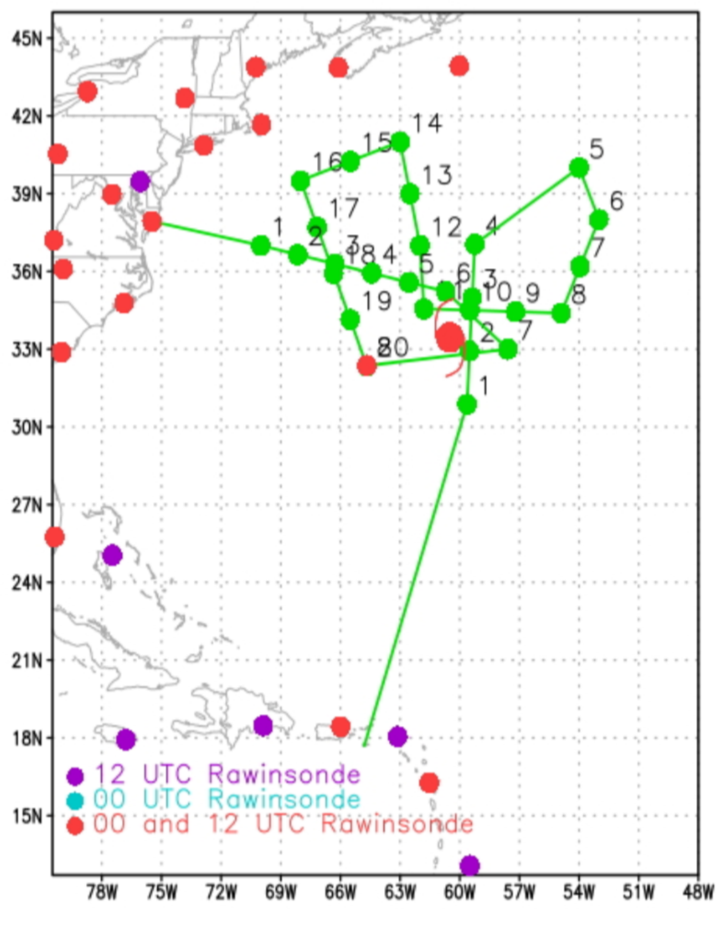


Figure EN-6. *Sample G-IV track investigating storm experiencing ET*

Flight altitude: At altitude

END STAGE EXPERIMENT
Pattern and Module Descriptions

Leg length or radii: Leg lengths depend on the size of the transitioning system. They should be of equal length, but can be shortened to the south, or due to land.

Estimated in-pattern flight duration: 8 h

Expendable distribution: ~20 dropwindsondes. During passes through the center, dropwindsondes will be deployed at each turn point and at evenly spaced intervals along each leg with optimal spacing near 90 n mi. At the TC-environment interface, dropwindsondes should be released every ~120 n mi.

Instrumentation Notes: None

SYNOPTIC FLOW EXPERIMENT
Pattern and Module Descriptions

Investigator(s): Jason Dunion, Sim Aberson (Co-PIs), Kelly Ryan, Jason Sippel, Rob Rogers, Ryan Torn (SUNY Albany), Eric Blake (NWS/NHC), Mike Brennan (NWS/NHC), Chris Landsea (NWS/TAFB) (Co-Is)

Requirements: No requirements: flown at any stage of the TC lifecycle

SCIENCE OBJECTIVE #1: *Investigate new strategies for optimizing the use of aircraft observations to improve numerical forecasts of TC track, intensity, and structure*
(Synoptic Flow)

P-3 Pattern #1: Synoptic Flow

What to Target: Sample the core and surrounding environment of the TC or pre-genesis invest

When to Target: Sample when model-targeting guidance indicates viable targets (e.g., see Fig. SY-1) that could positively impact the TC or pre-genesis invest track, intensity, or structure. Any intensity TC (or invest); no land restrictions; no specific take-off time requirements. If possible, this P-3 module should be conducted in coordination with **G-IV Pattern #1: Synoptic Flow**.

Pattern: For invests, any standard pattern that provides symmetric coverage (e.g., Lawnmower, Square Spiral, Figure-4, Rotated Figure-4, Butterfly). For TCs, fly any standard pattern that provides symmetric coverage (e.g., Figure-4, Rotated Figure-4, Butterfly, P-3 Circumnavigation).

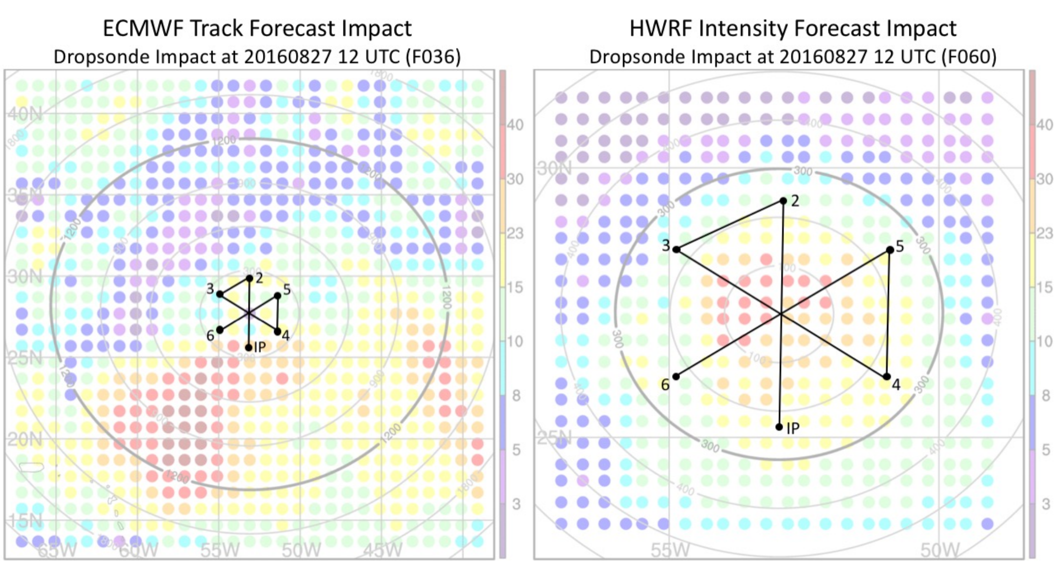


Figure SY-1. *P-3 Synoptic Flow pattern for a mission flown in 2016 Hurricane Gaston on 27 Aug 1200 UTC designed to impact the forecast for 29 Aug 0000 UTC. The plots show hypothetical reductions in (left) ECMWF position variance and (right) HWRF intensity variance due to assimilating GPS dropsonde data at each horizontal location. Warmer colors denote areas where GPS dropsonde data could most effectively reduce variance amongst the ensemble members.*

Flight altitude: 10–12 kft in the inner core and as high as possible in the near environment (>~80 n mi/150 km) to provide better vertical sampling by dropwindsondes that are deployed. If the P-3 is coordinated with the G-IV, P-3 altitudes greater than 10–12 kft may not be necessary.

Leg length or radii: Standard leg lengths (105 n mi) in TCs, but legs should be extended to reach the radius of 34 kt winds whenever possible (~125 n mi for North Atlantic hurricanes)

Estimated in-pattern flight duration: ~2.25–6.0 hr

Expendable distribution: Standard (10–20 dropwindsondes), although fewer may be used. Additional dropwindsondes are desirable in regions with high thermodynamic gradients or regions of downdrafts. AXBTs are not a mission requirement.

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits. All dropwindsonde data should be transmitted to the Global Telecommunication System (GTS) in real-time to ensure availability for assimilation into forecast models.

G-IV Pattern #1: Synoptic Flow

What to Target: Sample the near and peripheral environments of the TC or pre-genesis invest. If the P-3 is not available, the G-IV could also overfly or circumnavigate as closely as possible, the TC core or pre-genesis invest.

When to Target: Sample when model-targeting guidance indicates viable targets (e.g., see Fig. SY-2) that could positively impact the invest/TC track, intensity, or structure. Any strength TC (or pre-genesis invest); no land restrictions. If possible, this G-IV module should be conducted in coordination with **P-3 Pattern #1: Synoptic Flow**.

Pattern: Variable from storm to storm, dictated by regions that are identified using model targeting techniques. The over storm or near storm portion of the pattern could incorporate the following patterns: Figure-4, Rotated Figure-4, Butterfly, Lawnmower, G-IV Circumnavigation, G-IV Star pattern, or G-IV Star with Circumnavigation.

SYNOPTIC FLOW EXPERIMENT

Pattern and Module Descriptions

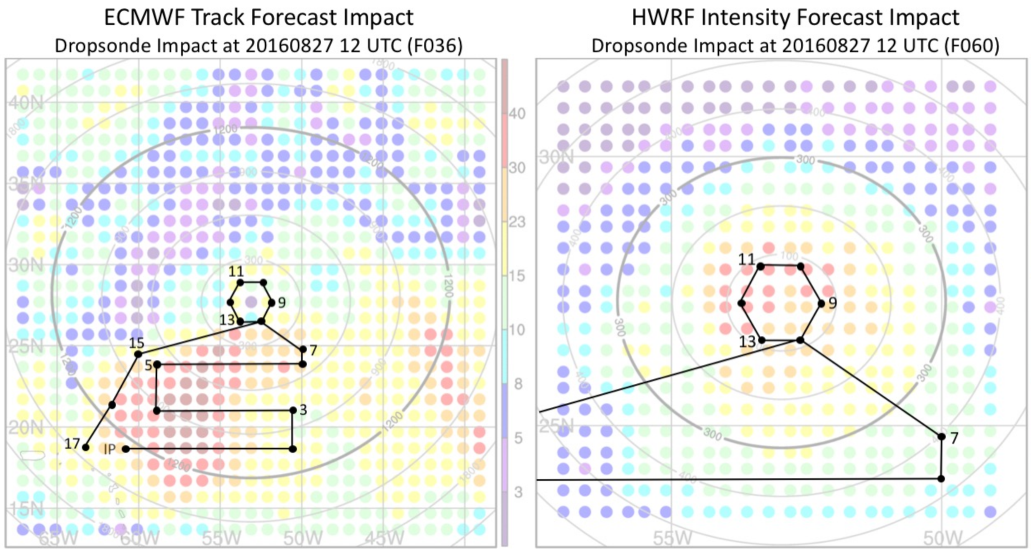


Figure SY-2. *G-IV Synoptic Flow pattern for a mission flown in 2016 Hurricane Gaston on 27 Aug 1200 UTC designed to impact the forecast for 29 Aug 0000 UTC. The plots show hypothetical reductions in (left) ECMWF position variance and (right) HWRF intensity variance due to assimilating GPS dropsonde data at each horizontal location. Warmer colors denote areas where GPS dropsonde data could most effectively reduce variance amongst the ensemble members.*

Flight altitude: 40–45 kft or as high as possible to provide better vertical sampling by dropwindsondes that are deployed

Leg length or radii: Standard leg lengths for over-storm patterns. For near-storm patterns, inner points and circumnavigation radii should be as close to the edge of the inner core convection as possible. This distance will be dictated by safety considerations, will typically range from ~60–120 n mi, and will require coordination between the HRD LPS and Flight Director on the G-IV.

Estimated in-pattern flight duration: ~2.5–7.5 hr

Expendable distribution: Standard in the pre-invest/TC inner core. For the near and far environments, ~2–3 degree spacing in quiescent regions and oversampling (~1–2 degree spacing) in model-indicated target areas.

Instrumentation Notes: Use TDR defaults. Use straight flight legs as safety permits. All dropwindsonde data should be transmitted to the Global Telecommunication System (GTS) in real-time to ensure availability for assimilation into forecast models.

OCEAN SURVEY EXPERIMENT
Pattern and Module Descriptions

Investigator(s): Jun Zhang, Nick Shay (Co-PIs), Rick Lumpkin (NOAA/AOML/Physical Oceanography Division [PhOD]), George Halliwell (NOAA/PhOD), Elizabeth Sanabia (USNA), and Benjamin Jaimes (U. Miami/RSMAS) (Co-Is)

Requirements: Categories 1-5

SCIENCE OBJECTIVE #1: *Obtain observations on TC-ocean interaction to improve flux parameterizations and to test coupled TC models* [TC-Ocean Interaction]

P-3 Pattern #1: Ocean Survey (Pre-storm)

What to Target: Region before storm passage based NHC's best track

When to Target: 48 hours prior to forecast arrival of the TC over the operating area

Pattern: Lawnmower, as in Fig. OC-1

Flight altitude: 6–8 kft preferable

Leg length or radii: 105 n mi

Estimated in-pattern flight duration: ~ 5 h

Expendable distribution: 50–60 aircraft ocean expendables (AXBTs/AXCTDs) spaced approximately 0.5 deg. apart. AXCP probes may be included if significant gradients (and thus currents) are expected to be observed.

Instrumentation Notes: Use straight flight legs as safety permits

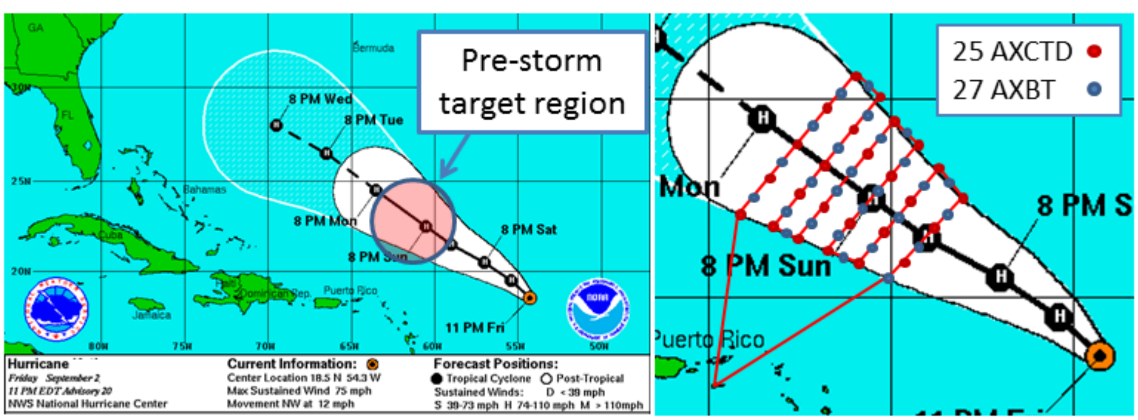


Figure OC-1: *Left: NHC official forecast track, which pre-storm ocean sampling region highlighted. Target region is centered ~48 hours prior to forecast arrival of storm. Right: P-3 flight track (red line) and ocean sampling pattern consisting of a grid of AXCTD/AXBT probes. Probes are deployed at ~0.5 deg. intervals.*

P-3 Pattern #2: Ocean Survey (In-storm)

What to Target: Sample the *core region* of a TC

When to Target: No constraint

Pattern: Standard Rotated Figure-4, as in Fig. OC-2

Flight altitude: 10 kft preferable

Leg length or radii: 105 n mi

Estimated in-pattern flight duration: ~ 5 h

Expendable distribution: 20–30 AXBTs in combination with dropwindsondes

Instrumentation Notes: Use straight flight legs as safety permits. Preferably flown with the WSRA.

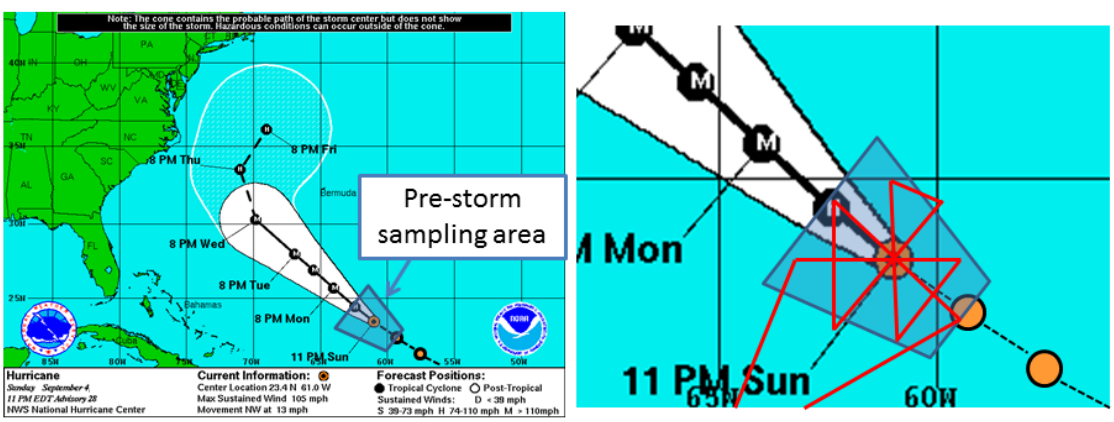


Figure OC-2: *Left: NHC official forecast track at time of in-storm mission, with pre-storm sampled region highlighted. Right: P-3 in-storm flight pattern centered on storm and over previously sampled ocean area. Typical pattern is expected to be a Rotated Fig-4.*

P-3 Pattern #3: Ocean Survey (Post-storm)

What to Target: Sample the same *pre-storm region*, with slight pattern adjustments made based on the known storm track

When to Target: Post storm

Pattern: Lawnmower, as in Fig. OC-3

Flight altitude: 8 kft preferable

Leg length or radii: 105 n mi

Estimated in-pattern flight duration: ~ 5 h

Expendable distribution: 60–70 aircraft ocean expendables (AXBTs/AXCPs)

Instrumentation Notes: None

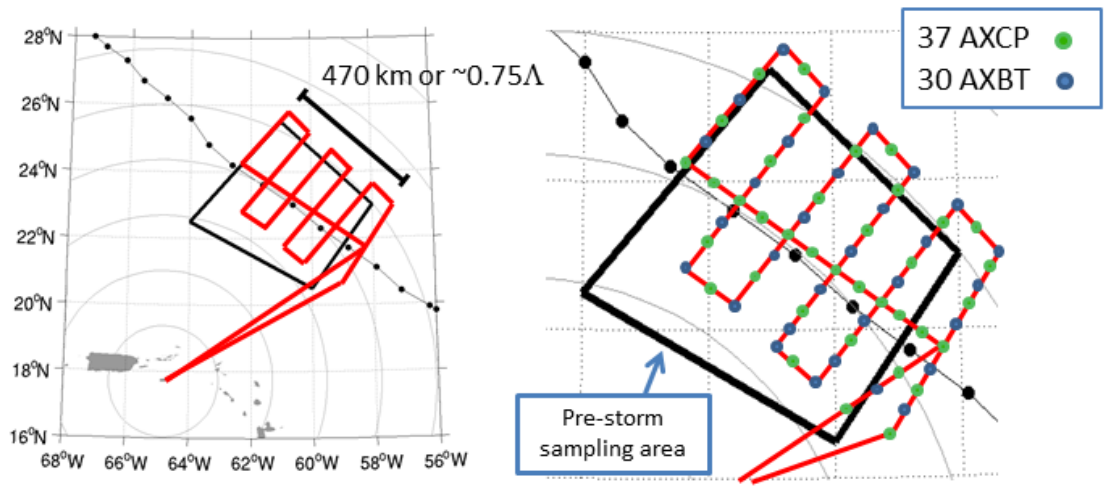


Figure OC-3: *Left: Post-storm ocean sampling flight pattern (red line), over previously sampled area (black box). In this example, the pattern extends around 470 km in the along-track dimension, or around 0.75 of a near-inertial wavelength. Right: Flight pattern with expendable drop locations, consisting of a combination of AXCP and AXBT probes.*

P-3 Pattern #4: Ocean Survey (Loop Current, Pre- and Post-storm)

What to Target: Sample the loop current and associated eddy field (Gulf of Mexico warm eddy)

When to Target: Pre- (1–3 days prior to storm passage over the loop current) and post-storm (over same area as pre-storm survey, 1–3 days after storm passage)

Pattern: As in Fig. OC-4

Flight altitude: 6–8 kft preferable (launched via free-fall chute)

Leg length or radii: 250 n mi

Estimated in-pattern flight duration: ~ 8 h

Expendable distribution: a total of 60–80 aircraft ocean expendables (AXBTs, AXCPs, and AXCTDs)

Instrumentation Notes: Use straight flight legs as safety permits

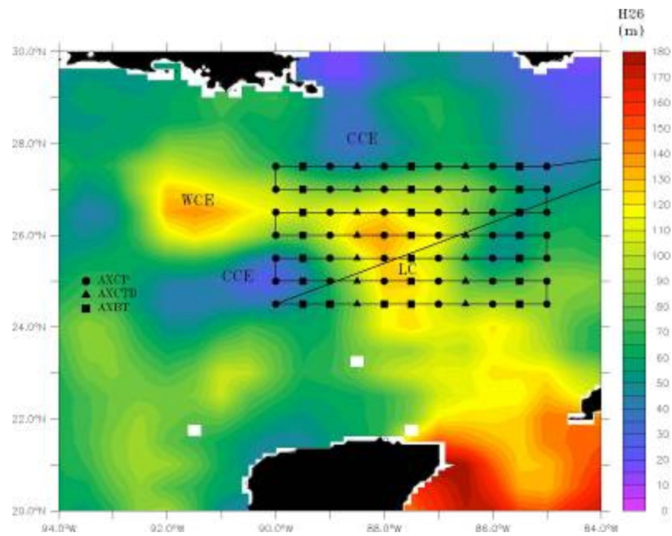


***Figure OC-4:** Typical pre- or post-storm pattern with ocean expendable deployment locations relative to the Loop Current. Specific patterns will be adjusted based on actual and forecasted storm tracks and Loop Current locations. Missions generally are expected to originate and terminate at AOC.*

P-3 Pattern #5: Ocean Survey (Loop Current, In-storm)

What to Target: Sample the *core region* of a TC and loop current eddy field

When to Target: In storm, no constraint

Pattern: Standard Rotated Figure-4, as in Fig. OC-2

Flight altitude: 8–10 kft

Leg length or radii: 105 n mi

Estimated in-pattern flight duration: ~ 4 h 45 min for Figure-4 + Rotated Figure-4 (45 n mi legs)

Expendable distribution: A total of 40 aircraft ocean expendables (AXBTs, AXCPs, and AXCTDs).

Instrumentation Notes: Use straight flight legs as safety permits.

P-3 Pattern # 6: Ocean Survey (Float and Drifter)

What to Target: Sample the *core region* of a TC

When to Target: In storm, no constraint

Pattern: As in Fig. OC-6

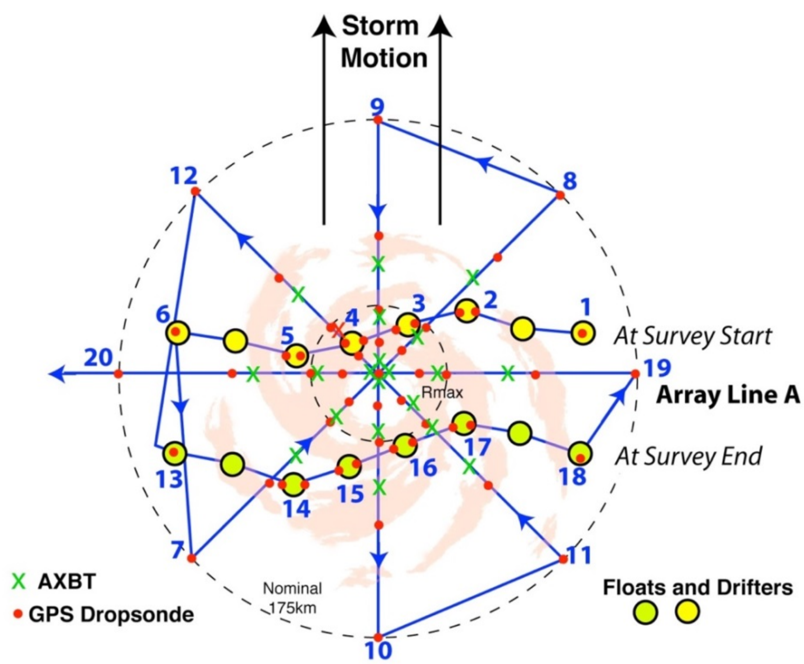
Flight altitude: 10–12 kft preferable

Leg length or radii: 105 n mi

Estimated in-pattern flight duration: ~ 4 h 45 min for Figure-4 + Rotated Figure-4 (45 n mi legs)

Expendable distribution: 56 sondes and 20 aircraft ocean expendables

Instrumentation Notes: Use straight flight legs as safety permits



Notes:
4 diameter lines through eye each with
9 dropsondes. At eye, 0.5 Rmax, Rmax, 2 Rmax, Line end.
5 AXBT. At eye, Rmax, 2 Rmax
2 float array lines each with
10 dropsondes. 2 at each of 4 floats, 2 Line ends.
Total: 56 dropsondes, 20 AXBT

***Figure OC-6**: P-3 pattern over float and drifter array. The array has been distorted since its deployment on the previous day and moves relative to the storm during the survey. The pattern includes two legs along the array (waypoints 1–6 and 13–18) and an 8 radial line survey.*

OCEAN SURVEY EXPERIMENT
Pattern and Module Descriptions

Dropwindsondes are deployed along all legs, with double deployments at the floats. AXBTs are deployed in the storm core.

Acknowledgments

The preparation of HRD's **Hurricane Field Program Plan** was a team effort. The authors would like to express their appreciation to: the HRD scientists that contributed information on specific experiments